Request	Date received	Requestor	Description	Status	Team Outbrief	UCIG outbrief
CaRI 001	3/17/21	xEVA Tools Team	The EVA Tools Team needs to have a list of materials, approved by the science community, that the Tools team will use to make the sampling tools for the Artemis Program. The list of accepted materials will enable finalizing tool designs.	Complete	5/3/21	9/23/21
CaRI 002	5/4/21	AES special study team	HEOMD's Advanced Exploration Systems (AES) Division is assessing options for Cold sample collection, stowage, return, and curation. They would like science input on a range of issues including science goals, sample types, sample volumes, and effects on samples under a range of collection and stowage conditions.	Partially complete	8/2/21	9/23/21
CaRI 003	7/13/21	HEOMD AES	The Crew Handheld Camera Working group is working to define a concept of operations and a set of requirements for the camera that will fly on Artemis missions, beginning with the first crewed landing. We request definition of science requirements for the crew handheld camera to determine whether any science requirements are beyond the scope of the current Handheld Camera development plans.	Complete	11/1/21	4/7/22
CaRI 004	7/26/21	ARES, Curation, xEVA Tools	We request contamination limits/requirements for Artemis in the areas where they are needed for returned geologic samples, since these requirements are currently not established or codified in a mission-level CC/CK document.	Complete	10/25/21	4/7/22
CaRI 005	7/26/21	xEVA Tools Team	The xEVA Tools Team wants CaRI to review traditional materials used to make EVA softgoods and ensure they are acceptable for Artemis.	Complete	10/18/21	4/7/22
CaRI 006	9/22/21	xEVA Tools Team	The xEVA Tools Team wants CaRI to review use of Lubricants and Koropon	Complete	2/7/22	4/7/22
CaRI 007	7/23/21	Sarah Noble (SMD)	CARI was asked to review a NASA internal document.	Complete	10/25/21	4/7/22
CaRI 008	1/3/22	xEVA Tools Team	The xEVA Tools Team is requesting CaRI guidance on possible sample (and correlated sampling tools) breakdown for based on the Artemis III SDT to aid in the conversation with HLS, Gateway, and Orion to ensure that proper volume and mass are allocated for sample return on Artemis III. Guidance on highest priority samples/sampling and containment tools.	Complete	4/7/22	4/7/22

Request #: CaRI 001
Requestor: xEVA Tools Team
POC: Adam Naids, adam.j.naids@nasa.gov, 610-731-1751
Date of Request: 3/17/2021
CaRI Adjudication Leads: Barbara Cohen and Juliane Gross

Background: The xEVA Tools team requires a list of acceptable materials for Artemis Geology Tools to be used during lunar surface EVAs so that tool designs can be finalized and evaluated in order to meet Design Review milestones. The EVA Tools Team understands that tool materials have implications for sample integrity and resulting science return. The xEVA Team has continuing dialog with personnel in ARES/JSC about the tool uses and operations; and the team has every reason to believe that doing things similar to what was done during Apollo and using materials that were used for Apollo sampling tools is an acceptable way forward. With approval of these materials the Tools team can start to finalize geology tool designs to meet Design Review Milestones.

Request: The EVA Tools Team has identified a list of materials that they desire to use to manufacture the sampling tools for the Artemis Program. A list of accepted materials will enable finalizing tool designs. Materials so far fall into three categories:

- Global Category 1 Material: materials used for sample intimate parts of the tools based on Apollo tool designs.
- Special Category 1 Material: materials that can be used for sample intimate parts of the tools based on Apollo tool designs. These are special situations that require different materials than are included in the Global approval.
- Global Category 2 Material: materials that can be used for non-sample intimate parts of the tools. Some requests are made from Apollo experience, and some are new.

Analysis: Contamination concerns arise when human activities cause a perturbation (usually an increase) in specific elements or compounds of interest to the analysis of those samples. The CAPTEM Lunar Science Subcommittee in 2020 (See Attachments) generated a table that encompasses the kinds of analyses the community performs on lunar samples, the elements of interest for those analyses, and the general elemental abundance to help the Artemis hardware design community understand what the lunar science community is most interested in.

Contamination components can be mixed into soils samples or transferred to particles and rocks; limiting these possible contamination occurrences as much as possible is important. Macrocontaminants like fibers shed from suits and gloves, torn pieces of samples bags, etc. are readily identifiable and separable. However, tiny particles of metal may be confused with native metal in lunar samples, and small amounts of material speared or transferred onto samples may not be recognizable as a separable component at all.

The primary concern with sample-intimate material for tools arises from trace metals and siderophile elements directly contacting the samples. Siderophile elements and trace metals underpin a wide range of scientific inquiry. It is useful to note that there are no Apollo samples that have any tool marks except a few where a chisel was used to chip them off a boulder, where

there are smear marks from the chisel. However, the Apollo materials list and procedures were generated before the current generation of very sensitive analysis equipment that can detect increasingly small abundances of metals and siderophile elements. Day et al. (2018) conducted a survey of lunar mare basalts and crustal rocks looking for contamination and found that that metal contamination plays a negligible role in the compositional variability of the siderophile and trace metal compositions preserved in these samples. They calculated that significant ($\gg$0.01% by mass) addition of stainless steel would be required to strongly affect the composition of the HSE, W, Mo, Cr, or Cu for most samples.

Small amounts of organic compounds, including hydrocarbons, urea, and amino acids, have been found in the Apollo samples, which may be contamination-derived or indigenous to the Moon and/or exogenous sources such as meteorites and solar wind. Potential contamination during sample acquisition, handling, or analysis was reduced during Apollo (and should be again during Artemis) by methodical reduction of organic contamination of the lunar samples on collection tools, sample return containers, curation facilities, and analytical laboratory equipment and chemicals (e.g., Flory and Simoneit, 1972). Multiple studies of returned lunar samples have characterized the organic materials and have largely concluded that contamination was minimal. Re-analysis in 2016 of Apollo 15, 16, and 17 samples stored under NASA curation since collection (Elsila et al. 2016) observed that amino acid abundances remained at low concentrations even after lengthy storage.

These sources of contamination are largely a concern on the exterior of samples. In all but the freshest lunar samples, billions of years of micrometeorite bombardment and solar wind impingement have "space weathered" the exterior surface. This weathering rind and its composition are of interest to scientists, but typically these studies are not affected by trace chemical contamination. The majority of lunar sample requests are for the interior of particles, where even limited amounts of surface contamination may be avoided in many analyses. In conclusion, there have been no widespread community concerns that sample analysis has been hindered by the tools or materials used in collecting, preparing, and curating the Apollo samples.

The CaRI team crosslisted the requested materials in tools list (see Attachments) with those materials approved for use in the Apollo samples (see Attachments) and others that are currently used in curation activities of the lunar sample collection. Most requested materials were approved for Apollo use and/or are in current curation use. Of the few that are not already in use, the compositions have similar levels of elements of potential concern (e.g., Cu, C, etc.), and therefore should pose no new issues. The team did notice a few instances where choices could be made.

Aluminum: Both Al 5356 and Al 4043 were requested and appear on the Apollo approved list. Al 5356 contains more elements overall compared to 4043; Mg and Cr is also higher, which could increase the potential for contamination of highland material. However, Apollo 16 was a highland sample and was not appreciably contaminated. Therefore, both Al types should be fine, but if a choice can be made, Al 4043 would be preferable.

Stainless steel: Both SS 17-4 and SS 17-7 were Apollo approved. Therefore, both SS types should be fine, SS 17-4 contains Ta and Nb. If a choice can be made to use SS 17-7, it is preferred over SS 17-4.

Teflon: Teflon was chosen for Apollo because of its gas permeability properties, its chemical and thermal resistance, and the fact that it can be chemically distinguished from naturally occurring organics. FEP and TEP Teflon were approved for Apollo use. PFA is a new Teflon, the only difference is it has an additional Oxygen atom (still has F and C). PFA is slightly stronger and is used in the current curation facility. Therefore, all the proposed Teflons should be fine.

Note that in nearly all metals, alloys, and materials compositions, a range is reported and frequently has an "other" or "residual" component (which Day et al. determined can contain trace elements of interest). Because the tools will not be returned to Earth with the samples, it is crucial to collect and curate coupons of each material from each manufacturer's batch for Contamination Knowledge (CK). Because these materials are already in wide use, it is not required that they be fully analyzed prior to use, but spot checks for material conformance to manufacturer composition would be prudent.

Recommendations:

1. CaRI approves the provided lists of materials in Global Category 1, Special Category 1, and Global Category 2 for use in sampling tools.

2. Given a choice, CaRI recommends using Al 4043 instead of Al 5356 and Stainless 17-7 over Stainless 17-4, however, both variants are approved if needed.

3. CaRI recommends the xEVA team develop a Contamination Knowledge (CK) process that may include procurement and curation of a coupon of each material, from each manufacturer batch, for contamination knowledge. The xEVA team should work with the relevant NASA curator to develop such a CK plan, which the CaRI team will be pleased to review.

4. CaRI recommends that the xEVA Tools Team continues to communicate with scientists in ARES and include them in Design Reviews and functional tests to help identify and communicate any issues regarding the tools materials and final design.

References:

Day, J. M. D., Maria-Benavides, J., McCubbin, F. M. and Zeigler, R. A. (2018), The potential for metal contamination during Apollo lunar sample curation. Meteoritics & Planetary Science 53, 1283-1291. DOI: 10.1111/maps.13074

Elsila J. E., Callahan M. P., Dworkin J. P., Glavin D. P., McLain H. L., Noble S. K., and Gibson E. K. (2016) The origin of amino acids in lunar regolith samples. Geochimica et Cosmochimica Acta 172, 357-369. DOI: 10.1016/j.gca.2015.10.008

Flory D. A. and Manned Spacecraft Center (1972) Experimental determination of potential lunar surface organic contamination in the lunar module descent-engine exhaust, NASA technical report; NASA TR R-389. NASA, Washington, DC. https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/N7228854.xhtml

Flory, D. A. and Simoneit, B. R. (1972) Terrestrial contamination in Apollo lunar samples. Space Life Sciences 3, 457–468 (1972). DOI: 10.1007/BF00926775

Simoneit, B. R., A. L. Burlingame, D. A. Flory and I. D. Smith (1969) Apollo Lunar Module Engine Exhaust Products. Science 166 (3906), 733-738. DOI: 10.1126/science.166.3906.733

Attachments:

CaRI Request
CaRI Decision Package - Global Cat I Material Approval_RevNC.pptx
CaRI Decision Package - Special Cat I Material Approval_RevNC.pptx
CaRI Decision Package - Global Cat II Material Approval_RevNC.pptx
Requested Materials Composition.pdf
CAPTEM lunar subcommittee_Artemis_Science-traceability-2020.pdf
Approved materials for Apollo.pdf
References

Request #: CaRI 002 A
Requestor: AES special study team
POC: Dina Contella, dina.e.contella@nasa.gov
Date of Request: 5/4/2021
CaRI Adjudication Leads: Jennifer Heldmann and Julie Mitchell

Background: HEOMD is assessing options for stowing and transporting cold samples from the lunar surface back to Earth. HEOMD is requesting definition of the temperatures and pressure ranges/thresholds for geology samples to be maintained and curated during transport via HEOMD systems to preserve the material for scientific analyses as well as the amount and types of samples needed for science assessment. Cold stowage is especially important for preserving information in samples containing lunar volatiles and ices. HEOMD's current plan is for cold stowage to be achieved through a phased approach, where early missions may have reduced or no capacity for cold stowage, but that this capability will become available (and increase) throughout the "sustainable" phase of Artemis.

Request: The AES study team presented two questions to CARI:

Cold Stowage Sample Return Question 1: At what temperatures and pressure ranges/thresholds must lunar geology samples be maintained and curated during transport via HEOMD systems to preserve the material for optimal scientific analyses? If optimal temperatures cannot easily be provided, are there other key 'interim' values to strive for during earlier missions (*e.g.*, can -80°C provide additional scientific value over ambient temperature and could it be achieved much earlier than colder temperatures)?

Cold Stowage Sample Return Question 2: What are the ranges of sample sizes/quantities and types (core vs. regolith) that must be accommodated for geology samples during transport via HEOMD systems to provide for scientific analyses (minimum and optimal)? Are there expected constituents that could be a toxicity hazard if released into the crew cabin, *i.e.*, might require additional levels of containment?

The CaRI Team recognizes that a thorough treatment of this request requires significant analysis and information, some of which is not yet available. The JSC Curation group (POC Julie Mitchell) has undertaken a set of laboratory and modeling experiments that will characterize the degree of alteration, both physical and chemical, for sample simulants under a range of storage conditions; these experiments will assess the efficacy of various temperatures, pressures, storage volumes, materials, etc. at preserving volatile-bearing samples [*Mitchell et al.*, 2018]. However, the timescale for completion and analysis of those activities exceeds the need-by date for this request; this report will be supplemented by laboratory measurements as validation of the modeling work and investigation of curation issues, which are best addressed through lab studies. We therefore broke out the requested deliverables into the following activities:

1. Science drivers for cold stowage report and science traceability matrix, initial indications from modeling work, description of planned lab work – this report (CaRI 002 A)
2. Fuller treatment of -80°C cold stowage case, including lab and more detailed modeling work, and implications for sample size, chain of stowage, and curation – supplemental report in November 2021 (CaRI 002 B)

3. Fuller results including wider range of stowage temperatures after lab and modeling activities – second supplemental report, estimated fall 2022 (CaRI 002 C)

Analysis:

1) Provide to HEO a set of desired science objectives that highlights the use of environmentally controlled sample curation.

Understanding the origins, ages, and evolution of lunar polar volatiles are key science objectives that benefit substantially from the use of environmentally controlled sample stowage and curation. Here, "volatiles" refers to compounds such as water, carbon dioxide, methane, *etc*. that exist primarily as vapor or liquid at and above Earth ambient conditions but condense at low temperatures.

Adsorbed species likely exist in lunar soils at all latitudes and seasons, though their abundance and form may vary [*Clark*, 2009; *Pieters et al.*, 2009; *Sunshine et al.*, 2009]. For example, water, carbon dioxide, methane, hydrogen cyanide, hydrogen, and minor amounts of hydrocarbons and other species can be liberated from Apollo soil samples when heated [*Friedman et al.*, 1970; *Gibson and Moore*, 1973] or released by micrometeorites [*Benna et al.*, 2019]. Condensed volatile deposits (*e.g.*, ices) are known to occur as subsurface and surface deposits in polar regions on the Moon. Surface volatiles (*e.g.*, frost) have been detected from orbit in patchy regions within some permanently shadowed regions (PSRs) [*Fisher et al.*, 2017; *Hayne et al.*, 2015; *Li et al.*, 2018]. Radar and neutron spectrometer data map hydrogen content (water equivalent hydrogen) and indicate more widespread volatile deposits in the surface or subsurface of both PSRs as well as transiently sunlit areas [*Campbell et al.*, 2003; *Feldman et al.*, 2000; *Nozette et al.*, 1996; *Sanin et al.*, 2012]. Thermal modeling based on orbital surface temperature measurements suggests that volatiles can be cold-trapped at relatively shallow depths (few cm to 10s of cm and deeper) both within and outside of PSRs [*Hayne et al.*, 2021; *Zhang and Paige*, 2009]. Temperature and age are key drivers that dictate the release or retention of volatiles; geologic terrains that are older and have been kept at lower temperatures can potentially have sequestered a higher abundance and a wider range of volatile compounds [*Deutsch et al.*, 2020; *Farrell et al.*, 2019].

There are multiple potential sources and sinks of lunar volatiles, including contributions from early volcanic outgassing, asteroid impacts, comet impacts, solar wind interactions with regolith, and/or ongoing meteoroid bombardment (see, for example, [*Anand*, 2011; *Anand et al.*, 2014]. Studying these compounds will allow us to determine whether volatiles were emplaced early in Solar System history and are ancient, have been delivered continuously throughout lunar history, or are a recent phenomenon (or some combination of the three). Once the volatiles were emplaced, the volatile deposits likely experienced subsequent modification and evolution. Processes such as solar wind sputtering, cosmic ray-induced chemical reactions, thermal diffusion, and/or orbital effects such as true polar wander (and the resulting volatile migration) may all affect the present-day observed volatile characteristics. The scientific value in understanding the origins, ages, and evolution of lunar volatiles extends beyond the Moon; understanding volatile delivery history and processes on the Moon is also key for elucidating processes occurring on additional airless bodies across the Solar System such as Mercury, Ceres, asteroids, and ocean worlds.

Studies of lunar polar volatiles are also key to enabling sustained human exploration of the Moon via *in situ* resource utilization (ISRU). The Artemis missions to the lunar south pole are designed to take advantage of the resources that may be found there, in particularly abundant sunlight, favorable thermal conditions, and access to potential stores of water and other volatile compounds. As with terrestrial mining practices, the exploration of such potential resource deposits requires an understanding of the origin of the volatiles, their lateral and vertical distribution, form, and abundance [*Cannon and Britt*, 2020; *Casanova et al.*, 2020]. These fundamental science goals will build the necessary predictive capabilities to enable assessments of lunar volatile resources, such as the replenishment rates, locations, grade, and processing needs, and will allow for optimal design and operation of ISRU architectures and hardware elements.

In addition to the host of community reports, two NASA-commissioned reports, the Artemis III (AIII) Science Definition Team (SDT) Report [*Weber et al.*, 2020] and the Lunar Water ISRU Measurement Study (LWIMS) [*Kleinhenz et al.*, 2020] defined goals for volatiles science and preparation for ISRU, many of which require cold/cryogenic sample return. The CaRI committee adopted the goals of the Artemis III SDT for consideration in this report. We note, however, that the AIII SDT report was focused on the first crewed lunar landing, and subsequent landed missions during the 'sustainable' phase of Artemis should have increased capabilities for cold sample return (*e.g.*, mass, temperatures, sample volumes, *etc*).

For the purposes of this CaRI 002 assessment, below are the relevant AIII SDT Investigations regarding cold sample stowage and transport.

Investigation 2a-1: Identification of surface frost composition. Current ultraviolet and near-infrared spectral data along with temperature measurements combine to indicate the presence of discontinuous surface water ice frosts in the polar regions of the Moon. Confirmation of water ice as well as detection of additional volatile components within exposed frosts can be accomplished during the Artemis III mission with surface measurements and sample collection in regions accessible by humans. Regions to be examined include PSRs, micro PSRs, and transiently shadowed regions. Required measurements include spectral identification of volatiles and their relative abundances (*e.g.*, H_2O, CO_2, CH_4, H_2S, NH_3, SO_2) and analysis of isotopic ratios such as deuterium to hydrogen ratio (D/H). *In situ* surface measurements and sample return are required.

Investigation 2a-2: Identification of surface frost locations in spatial context. Local surveys of frost environments are important for understanding the controlling environmental variables regarding frost deposition and retention. PSRs, micro PSRs, and transiently shadowed regions outside of the disturbed landing zone should be surveyed. Increased mobility is better for increased coverage and assessment, but with appropriate tools astronaut walking distance is likely sufficient for initial identifications of surface frost locations. Larger scale regional surveys of surface frost utilizing *in situ* measurements, but without a rover capable of traversing distances on the km-scale will be difficult. If *in situ* tools are optimized for frost assessment, only surface measurements are required and thus no subsurface access is needed for this Investigation. *In situ* surface measurements coupled with surface sample return is required.

Investigation 2a-3: Temporal variability of frost. Although not all the variables affecting the presence or absence of surface frost are known, it is clear the average and diurnal temperature of the surface is key. Temperatures affecting the stability and presence of frost on the lunar surface are expected to vary over diurnal and seasonal timescales. Monitoring the temporal variation of surface frost will require longer term measurements than afforded by the Artemis III EVA

durations. Frost surveys conducted by the astronauts would benefit from landing in the early morning to assess time of day changes in frost deposition and location. Such initial measurements can be made *in situ* by astronauts and through targeted sample collection. The deployment of longer-term instrument packages is required for time-dependent measurements over a minimum of one lunar day/night cycle.

Investigation 2a-4: Speciation of surface hydrogen. Data from the Lunar Prospector and LRO missions have indicated areas of enhanced hydrogen in the lunar polar regions. However, these datasets cannot determine the form of this hydrogen, which may contain multiple H-bearing compounds, each with different origin and stability constraints. Measurement of the speciation of surface hydrogen can be made from different locations in the vicinity of the Artemis III lander outside of the landing (contamination) zone. Evaluation of the diversity of hydrated species is also important to better utilize remote sensing observations and as constraints for space weather processes on surface materials at the poles. Measurements are preferred in both sunlight and shadow. Coordinated *in situ* surface measurements and surface sample collection is required.

Investigation 2a-5: Understand surface hydrogen speciation spatial variability. The lunar polar hydrogen observed with remote sensing data indicates significant spatial variability across the lunar surface, although obtained at low spatial resolution. Measurements of surface hydrogen across spatial scales over 1 km or more are desired to characterize the lateral variation of hydrogen and its associated abundance and speciation. Measurements are dependent on local geology and are preferred in both sunlight and shadow. *In situ* surface measurements and surface sample collection is required.

Investigation 2a-6: Spatial distribution of subsurface hydrogen. Data from the Lunar Prospector and LRO missions have been used to model areas of enhanced subsurface hydrogen in the lunar polar regions. The low spatial (lateral) resolution of these datasets coupled with uncertainties in hydrogen depth distributions and the inability to determine the form of the hydrogen from these measurements requires direct characterization of the hydrogen in both lateral and vertical dimensions on the Moon. Measurements both within and outside of PSRs and in varying ice stability regions (dry, deep, shallow, surface) to assess subsurface spatial variations are required to adequately characterize the hydrogen deposits. Measurements to ~1 m depth are necessary in order to validate and extend existing hydrogen data obtained remotely. Characterizing the lateral H variability requires multiple measurements across the lunar surface and hence mobility. The assumed initial mobility afforded by Artemis III is reasonable to achieve these goals (to ~1000 m distances). Subsurface samples (cores and/or discrete samples collected at varying depths up to 1 m) collected without significant de-volatilization coupled with *in situ* measurements are required.

Investigation 2b-1: Origin of the polar volatiles. This Investigation can be accomplished with measurements from PSRs and transiently lit areas where near subsurface temperatures have allowed for an accumulation of volatiles. Characterizing the concentration, chemistry, and temperature of volatiles is important for informing the origin of the volatiles. In addition, measuring stable isotopic ratios (*e.g.*, D/H, $^{18}O/^{16}O$, C, N, S, *etc*.) can distinguish between solar wind, cometary, and endogenic end members, and place constraints on the relative contributions of each potential source. *In situ* measurements coupled with sample collection (including surface samples and subsurface core samples) with minimal volatilization are required.

Investigation 2c-1: Distribution of water/OH within a PSR. Addressing this Investigation requires a lateral assessment of water/OH with a PSR coupled with vertical documentation of 0.5% water-equivalent H (+- 50%). Obtaining samples at intervals of 10-20 cm to a depth of 1 m or more are necessary. These measurements require subsurface access without significant de-volatilization and will necessitate *in situ* surface measurements as well as sample collection. The timing of measurements and sample collection is also critical to document since the local thermal environment, even in PSRs, is subject to diurnal and seasonal temperature changes that can affect the mobility of volatiles on those timescales. If access to a PSR is not available, such measurements at a documented micro-cold trap may provide valuable initial information.

Investigation 2d-1. Speciation of surface hydrogen. The lunar surface is a dynamic environment exposed to the solar wind, UV, and other radiation, and subject to space weathering processes of exposed and derived surface materials, including volatiles. Measurements to characterize these products and space weathering processes and effects can be performed on the Artemis III mission outside of the landing zone (where the surface is disturbed and likely contaminated). Increased mobility is optimal for improved contamination control, although astronaut walking distance is likely sufficient for initial measurements. Uppermost soil samples are required from a suite of diverse, well documented terrain with *in situ* volatile measurements before and after sampling. No subsurface access is required. Measurements and samples both in sunlight and shadow are preferred.

Investigation 2f-1: Identify exploration-induced variations on volatile composition, form, and distribution on the lunar surface during sample collection and transport, during curation and analysis, and from landed activities. Measurements to characterize the impacts of lunar surface exploration should be made in vicinity of the Artemis III lander, including measurements at varying distances from the site(s) of surface mission activity. *In situ* measurements as well as the deployment of long lived instrument packages are recommended to characterize both initial and temporal changes in the lunar polar volatile environment as well as to assess environmental impacts during and after lunar ascent from the surface.

2) Provide to HEOMD a description of the intended volatile species to be studied that require environmental conditioning.

Key compounds, their relative abundances, and their isotopes, will be used to determine the origin, age, and evolution of lunar volatiles. Potential sources and major associated volatile species include:

- Lunar interior/volcanic origin (H_2O, CO, H_2, H_2S, COS, S_2 with an emphasis on the sulfur compounds);
- Asteroid and micrometeorite contributions (H_2O, noble gases, isotopes of C, H, O, N);
- Comet impacts (complex organics, H_2O, CO, CO_2, H_2S, NH_3, CH_4, C_2H_6, CH_3OH; noble gases, isotopes of C, H, O, N);
- Solar wind (H_2, noble gases, isotopes of C, H, O, N);
- Anthropogenic contaminants such as propellants, spacesuit/vehicle leakage, crew waste (a wide range of organic and volatile compounds and their derivatives).

Our only ground-truthed measurement of volatiles sequestered in the lunar south polar region are from the Lunar Crater Observation Sensing Satellite (LCROSS) impactor mission into Cabeus crater, a ~40-K PSR near the lunar south pole. Volatiles identified in the impact plume include OH, H_2O, CH_4, SO_2, H_2S, NH_3, C_2H_4, CO_2, and CH_3OH [*Colaprete et al.*, 2010]. The presence/composition and abundances of the LCROSS volatile species should be measured in returned samples since these are known to exist on the Moon in at least one location.

The lateral and vertical distribution of volatiles is also important to measure (*i.e.*, multiple samples collected from different locations and depths). Small-scale (meters) lateral distribution is indicative of variance from impact gardening processes and would constrain the effects of thermal protection of volatiles from ejecta blankets. Subsurface volatile distributions reflect subsurface thermal regimes, thermal diffusion, *etc*., which in turn affect the sequestration of different volatile species on and within the lunar regolith. Discrete lenses or layers of volatiles, ice blocks, *etc*., may indicate episodic depositional events while homogenous surface deposition would indicate different processes of more ubiquitous deposition [*Cannon et al.*, 2020]. Additionally, the layering of impact ejecta could provide thermal shielding to insulate volatiles, providing stable temperatures and therefore thermodynamic/chemical stability.

Temporal variability will also help to discern the relative proportions of volatiles that were deposited in single large events, by the solar wind, or due to diurnal migration across the lunar surface. Samples collected from the same location, at different times, will be crucial to characterizing the movement patterns of lunar volatiles as lighting conditions change throughout the lunar day and years.

3) What are the Temperature-Pressure-Time thresholds for different materials and describe above what temperature/pressure/time of exposure would the science integrity be compromised for these materials.

The CaRI assessments of temperature-pressure-time constraints for the volatile-bearing lunar samples assume that samples intended for volatiles science will be sealed immediately upon retrieval at the lunar surface to prevent immediate sublimation and interaction with the cabin atmosphere in which they will be transported. Figure 1 shows the sublimation temperature of the volatile species of interest at lunar surface pressure.

After sealing, any volatile-bearing sample that is allowed to warm above its original temperature (*e.g.*, the native lunar temperature where the sample was collected) will experience phase changes (*e.g.*, transition from a solid form to gas and/or liquid). The nature and extent of these phase changes will depend on the compound, its abundance, its packing density/pressure (*i.e.*, how much headspace is available in the sample container), the size of the sample, and the degree of heating experienced by the sample. The likelihood of chemical reactions between the volatiles, and between the volatiles and rock/regolith portions of the sample(s) is the highest if aqueous-phase chemical reactions are allowed to take place; that is, if the triple-points of H_2O (6.1 mbar, 0.01°C) or CO_2 (5.1 bar, -56.6°C) are reached.

In some cases, measurement and modeling of the volatile species in returned samples can be accomplished in the gas phase (*e.g.*, head space gas, as will be measured on the ANSGA Apollo 17 sample) and/or adsorbed onto different sites on the sample. However, **the more the sample stowage conditions differ from the native collection conditions, the more the**

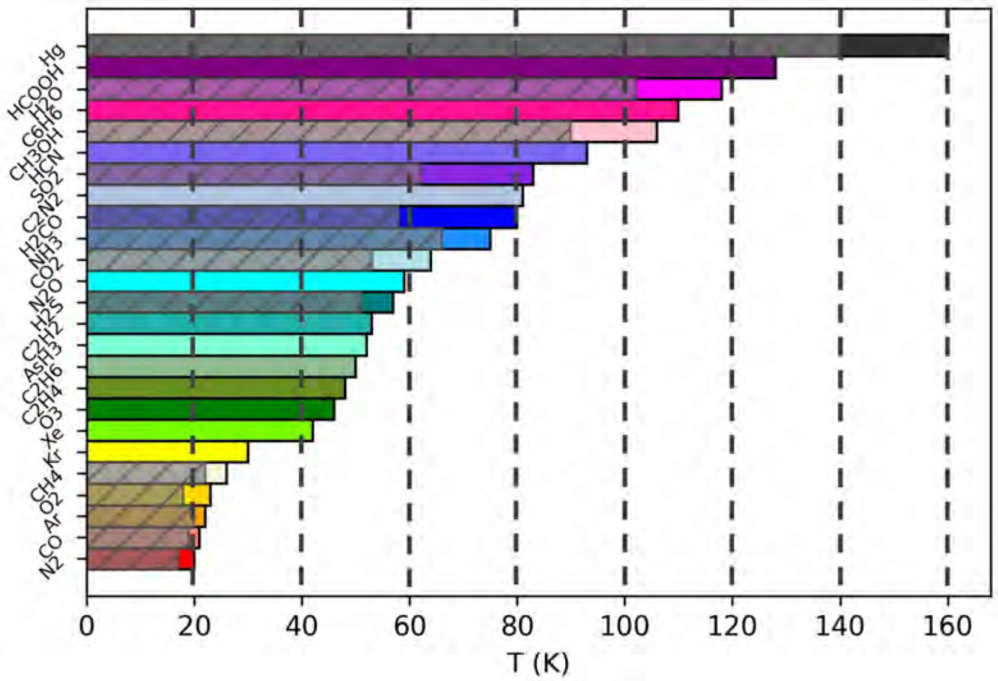

Figure 1. Sublimation temperatures of lunar volatiles of interest [*Fray and Schmitt*, 2009] as a function of temperature at lunar pressure (prepublication work by Mitchell et al.). Hashed bars are from [*Zhang and Paige*, 2009].

volatile nature will change and the less direct the link to their native form. In some cases, this may also be actively detrimental: for example, if liquid water forms in the sample, water-rock reactions even at low temperatures may erase compositional information in the original sample [*Engel et al.*, 1994; *McAdam et al.*, 2008] or initiate the formation of acids (*e.g.*, H_2SO_4 – sulfuric acid) that could degrade both the sample and container. Therefore, the primary constraint for any lunar sample transport is to keep the pressure-temperature (P-T) conditions well below the triple-points of water or CO_2. "Well below" is a margin that needs to be quantified with future work, but maintaining the sample in an acceptable P-T phase space should be a requirement pending laboratory testing of the P-T behavior of lunar volatile simulants. This margin is needed to account for the possible freezing-point depression that may occur due to the presence of soluble compounds in the sample (*e.g.*, salts) that alter the P-T phase diagram of water and CO_2.

Some gas-solid chemical reactions may also occur if the sample is below the triple-point of water and CO_2. However, these reactions will occur at a lower rate than aqueous-phase chemical reactions and are therefore considered lower risk for significant sample alteration, given what is currently known about anticipated sample transit times from the Moon to Earth. Laboratory testing is required to quantify the reaction rates under flight-like and lunar-like conditions for lunar volatile analog materials.

4) What is the minimum volume of sample required within these parameters in order to meet scientific objectives?

Sealed core samples and sealed surface samples are ideal for addressing the high-priority science questions pertaining to lunar volatile characterization as outlined above. Compositional and physical properties, abundance, and distribution (lateral, vertical, and temporal) of H-bearing and other volatile species of the regolith are key measurements to achieve these objectives. Further, characterizing the concentration, chemistry, and temperature of volatiles is important for determining their origin. Measuring stable isotope ratios (*e.g.*, D/H, $^{18}O/^{17}O/^{16}O$, $^{14}C/^{12}C$, N, S, *etc*.) can distinguish between solar wind, cometary, and endogenic end members, and place constraints on the relative contributions of each potential source. Sample collection (including sealed surface samples and sealed subsurface core samples) with minimal alteration is required.

Thus, if feasible, sealed core samples should remain as close to the sampling temperature as possible to preserve variations in volatile content and/or chemistry within individual core sections. These samples should be sealed on the surface of the Moon and should remain sealed until they are opened for preliminary examination by NASA's Astromaterials Acquisition and Curation Office.

In and around PSRs and micro-cold traps, it is predicted that there will be volatiles in the near-surface regolith, and potentially ice ("frost") deposits on the surface. There is also the potential to collect regolith that has been contaminated by the exhaust of the descending lander, spacesuit degassing, or other anthropogenic sources, all of which are important for both studies of lunar volatiles and studies of human-induced changes to the lunar surface. Appropriate surface samples can be quickly and easily collected using a scoop and should be contained separately in individually sealed containers. Keeping the samples frozen at temperatures as close to lunar ambient as possible would permit a greater preservation of the original chemical speciation of the volatiles as they were sampled. At a minimum, two sealed surface samples should be collected.

The volume of these samples depends on the porosity of the regolith and how the samples are packed into each sample container. The sizing of the sample containers should be based on these recommended sample masses and estimates of regolith porosity based on Apollo sample data (with the caveat that PSR regolith density may be different than observed at Apollo sites). Required sample volume is also dependent upon the returned sample mass. The abundances and types of volatiles present will also affect sublimation and associated rates of phase change for different species. Numerical modeling and laboratory testing are required to quantitatively constrain the trade space among these key variables (*e.g.*, sample mass, volume, temperature, volatile abundance, *etc*).

Table 2 in the AIII SDT report lists a nominal sample return allocation of 20 sealed sample containers and eight "cores," distributed between drill cores and drive tubes per Table 1 below. Given that these are values for a notional Artemis III mission, and capabilities for both returned mass and cold stowage temperatures should be increasing with future missions, the AIII SDT report values are the bare minimum amounts of sample return for initial missions with a freezer. In lieu of an SDT report for the "sustainable" missions, we recommend that future estimates take into account the recommendations made by CAPTEM for returned sample mass, which exceed the downmass and upmass planned for Artemis III [*Curation Analysis and Planning Team for Extraterrestrial Materials*, 2007]. This forward work can be undertaken when the increased downmass and upmass allocations are further constrained and understood.

Table 2 of the AIII SDT report lists a minimum return manifest that includes zero sealed samples and only four "cores" (drive tubes and drill cores); it is likely that this "worst-case"

scenario for lunar volatiles preservation will be what is implemented for the first landed Artemis mission (Artemis III). If this minimum number of sealed samples would be able to be accommodated (*e.g.*, the freezer is too small to meet the nominal volume), then a slightly smaller freezer could be accommodated by Science for *only the short term* with the caveat that this would be a temporary solution; science requirements must be considered as drivers for the evolution and increase of Artemis capabilities within HEO. Future freezers should be able to accommodate the full suite of Artemis III SDT recommended samples and more, along with phasing in the capability for cryogenic storage/sample preservation from ultra-cold PSRs. Until a guiding report is made for sustainable missions, we recommend maintaining the same ratio of unconditioned-to-conditioned samples for future missions as mass, volume, and power allowances increase.

Table 1. Mass allocations and sample types for cold stowage sample return.

	Minimum Initial Mission Threshold
Double Drive Tubes	2
Mass (kg)	20
Drill Cores	1
No. Sections per Core	4
Mass (kg)	20
Sealed Surface Samples	20
Mass (kg)	20
Total Sealed Mass (kg)	60

5) Assess the scientific implications of using existing solutions for cold conditioning of -80, -150, -180, -196 °C, including whether there is value for conditioning geology samples if only the -80°C capability is available.

The CaRI team has been asked to assess cold conditioning temperatures based on existing capabilities for cold sample return primarily based on Space Shuttle and ISS heritage. For example, on the ISS, the crew health/biology samples are stored and transported at -80°C [*Garrett-Bakelman et al.*, 2019]. Therefore, -80°C is a reasonable target for crew health/biological samples, although warmer temperatures (4°C or -20°C) are permissible for biologic samples that will be analyzed relatively quickly. Blood/urine/crew samples can be stored in liquid nitrogen, so storing these samples at lower temperatures than -80°C is not an issue for most of the samples requiring conditioning (except for ensuring that vials/containers are compatible with low temperatures and won't shatter).

For lunar volatile samples, the ability of a freezer to successfully preserve a lunar volatile-bearing sample is highly dependent on the temperature of the location where the sample was originally collected. For example, a sample from a 40 K (-233°C) PSR will be much more sensitive to alteration based on the greater variety of volatiles that can be sequestered at lower temperatures and will therefore likely experience more alteration at -80°C than a sample collected from a 100

K (-173°C) PSR. Therefore, colder stowage temperatures generally preserve more volatiles with less alteration.

Laboratory testing will assess the chemical and physical stability of volatiles in a lunar simulant material across different temperature regimes. The data from these tests will aid in systematically determining the effects (sublimation, condensation, chemical and isotopic fractionation and interaction) of different sample storage temperatures for a range of plausible lunar volatile samples. While those experiments are ongoing, we have done two assessments to aid the HEO assessment of the scientific implications of returning initial cold-conditioned samples at -80°C.

First, a member of the cold curation team at JSC performed modeling work to assess the behavior of a notional sample based on LCROSS at a range of temperatures, and whether the sample will meet/exceed the triple-points of water and other compounds in flight. This preliminary analysis demonstrates that the triple points of several compounds are reached at -80°C: CH_4, C_2H_2, CH_3OH, and H_2S. In particular, the triple point of H_2S occurs at -85°C, which is very close to the ISS heritage temperature of -80°C. Given that H_2S was the second most abundant volatile detected by LCROSS (after water), avoiding the triple point of H_2S could have significant implications for sample preservation and thus stowage at -85°C should be strongly considered, if feasible. Liquid H_2S has not been studied as a solvent extensively; however, Wilkinson (1931) studied it for a representative suite of inorganic and organic compounds. Based on his work, we estimate that inorganic compounds will be largely unaffected by liquid H_2S, with the exception of chlorine and chlorides. Chlorides are major compounds used in the study of planetary volatiles (for chloride analyses). Lawrencite, akaganéite, and possibly apatite would be affected [*Shearer et al.*, 2014]. These minerals are key to the studies of planetary volatiles and interiors, and their dissolution would be a major impact to lunar volatiles science. Finally, alcohols (e.g., methanol, found by LCROSS) and organics would likely dissolve in H_2S and react in solution to form alteration byproducts.

Further detailed modeling is needed to incorporate other possible compounds beyond those detected by LCROSS; therefore, the results described in this report should be taken as preliminary. In addition, laboratory testing is needed to validate these initial results as well as to assess possible gas-phase interactions that would adversely affect the ability to reconstruct original volatile contents at different stowage temperatures.

Second, the CaRI team conducted a high-level assessment of the science goals in Section (1) against a matrix of stowage/return temperatures for three different case studies. The three different cases considered included:

Case a) a sample location similar to a deep PSR, where high volatile abundance occurs in the subsurface, the volatiles have a cometary-like composition (similar to LCROSS), and volatiles have been stored *in situ* at very cold temperatures for billions of years.

Case b) a sample location similar to a micro-PSR or a transiently-shadowed region (TSR), where the cold trap is relatively small in radius and depth (a few meters or less), the sample may have experienced higher temperatures over geologic time, and the volatile component may be less abundant and/or less diverse.

Case c) a sample location intended to sample surface frost, which is geologically young and primarily composed of water ice.

Our sampling assumptions were that crew would visit a location where water ice is thought to be stable, but the crew would not know *a priori* whether ice actually exists at the location. The crew would drill or auger down from the surface to 1 m depth and collect a core sample (Cases a and b), or a surface scoop followed by a core (Case c). The sample collection itself would not include any cryogenic capabilities (*i.e.*, the drill would not be actively cooled, but operations could be set so as to not overly heat the regolith during drilling). The sample would be retrieved and hermetically sealed immediately on the lunar surface, then stowed at a set temperature such that the sample is not heated significantly during transport to the HLS (Human Landed System). The samples would be stored at the stowage temperature for ~2 weeks prior to splashdown on Earth, recovery, and curation operations. The sample would be opened in the NASA JSC curation facility, headspace gases would be retrieved, and any unstudied portions of the sample would be cryogenically preserved in the curation facility.

For these cases, we assessed four different stowage/return temperatures: uncontrolled temperature, -20°C (heritage Apollo sample freezer), -80°C (heritage ISS freezer), and -200°C (liquid nitrogen / cryogenic freezer). We qualitatively assessed how well each stowage temperature would enable the science objectives to be met via terrestrial laboratory analyses using the samples stored at the set temperature in order to illustrate of the types of science that could be accomplished (Table 2). Detailed analysis for each scenario, objective, and temperature could be done that may change each assessment slightly, but overall, this assessment demonstrates that uncontrolled temperatures thwart the majority of volatile science that could be accomplished by retrieving such samples from the Moon. In general, heritage geologic and biologic freezer storage temperatures will allow some combination of measurement and modeling to proceed even as volatiles may change form (*e.g.*, sublime and interact with each other) within the sample container. Because the samples from the Moon have been formed and stored in very cold environments, cryogenic sample return is required to preserve them in their pristine states, and this methodology is the best way to understand the form, abundance, distribution, and isotopic characteristics of lunar volatiles. The information that can be obtained from well-curated volatile samples from the Moon will benefit not only our scientific understanding of the lunar volatiles, but will also be critical to design follow-on sample strategies and ISRU architectures.

Temperature-induced alteration may affect several types of potential future analyses, with the extent dependent on the difference between the original sample temperature and the temperature at which that sample is stowed in flight. Although many volatiles will sublime to the gas phase at -80°C, some solid ice may remain, particularly in the interior of the sealed core, and a temperature of -80°C could minimize gas diffusion depending on the size of the sample, thickness of the sample's regolith lag deposit to preserve interior ices, and original abundance of volatiles. Preserving solid ice will allow for understanding the stratigraphy and distribution of volatiles, which are key observations required to address multiple high-level science objectives. As described above, keeping the sample below the triple-point of water is also essential for keeping the sample unaltered for additional science investigations. Thus, returning the samples at -80°C is of greater scientific value compared to a non-cooled return.

However, a temperature of -80°C would be insufficiently cold to enable all high-priority scientific studies. Volatiles that sublime to the gas phase at -80°C (*e.g.*, NH_3 and HCN) may react with each other, making it impossible to fully identify and quantify the original volatile composition; lower temperatures would keep more of these species in the solid phase and reduce/slow chemical reactions. Similarly, isotopic fractionation and exchange during sublimation

and in the gas phase is a concern that can complicate future measurements and interpretation; again, lower temperatures will reduce these effects. Future laboratory studies are required to fully understand and quantify these effects as a function of sample composition, ice form and stratigraphy, storage temperature, *etc*.

Table 2. Qualitative assessment of effect of stowage temperature on science implementation for lunar volatile objectives.

Artemis III SDT Investigation	T=Uncontrolled			T=-20°C			T=-80°C			T=-200°C		
	Case a	Case b	Case c	Case a	Case b	Case c	Case a	Case b	Case c	Case a	Case b	Case c
Investigation 2a-1: Identification of surface frost composition												
Investigation 2a-2: Identification of surface frost locations												
Investigation 2a-3: Temporal variability of frost												
Investigation 2a-4: Speciation of surface hydrogen												
Investigation 2a-5: Surface hydrogen speciation variability												
Investigation 2a-6: Spatial distribution of subsurface hydrogen												
Investigation 2b-1: Origin of the polar volatiles												
Investigation 2c-1: Distribution of water/OH within a PSR												
Investigation 2d-1: Speciation of surface hydrogen												
Investigation 2f-1: Identify exploration-induced variations												

Key

	Substantially or fully meets (for individual samples, though usually multiple samples are required)
	Partially meets or imperfectly addresses (for example, modeling needed to understand initial conditions, non-unique solutions may exist)
	Poorly meets or can't accomplish
	Not applicable

6) Describe criteria for assessment of successful return of cold curated samples.

Based on the initial results and assessment in this study, CaRI recommends the following guidelines for volatile sample return and cold stowage to ensure successful scientific studies:

- Samples intended for lunar volatile study shall be sealed at the lunar surface immediately upon their retrieval.
- The pressure and temperature conditions of the sample(s) shall not reach the triple-points of water or CO_2 after sampling, including after splashdown/during recovery operations, and prior to entry into the curatorial facility.
- The maximum temperature experienced by the sample shall be measured and monitored throughout collection, stowage, return, and curation.
- The pressure in the sample container shall not equilibrate with the cabin atmosphere. The volatiles shall not be released into the crew cabin (relevant for both science and human health and safety purposes).
- The storage temperature for the sample, *e.g.*, "-80°C," shall serve as a maximum temperature for cold stowage for initial missions only. Sustainable missions shall focus on accommodating sample stowage at cryogenic temperatures and increasing sample mass to accommodate the Artemis III SDT maximum sample return masses.

The full success of lunar volatile sample objectives relies not just on samples, but also includes *in situ* characterization of volatile-bearing samples. Such characterization includes compositional measurements, imaging, and environmental (*e.g.*, temperature, lighting, *etc.*) measurements that will characterize the samples as they exist at the lunar surface, aid in selecting sample collection locations (especially given the known heterogeneity of lunar volatile deposits), assist in unraveling alteration during the collection, transport, and curation processes (especially with sample return capabilities at temperatures substantially above ambient lunar temperatures), and provide key information for assessing sample hazards associated with the presence of toxic volatiles. A wide range of instruments may be used to make *in situ* measurements to support science objectives [*Lunar Exploration Analysis Group*, 2018]. *In situ* instruments should also be capable of detecting key volatiles that are of concern to crew and curator health and safety. Additionally, visual imaging at millimeter-scale resolution will be necessary for collected samples to characterize *in situ* stratigraphy and form of ice (*e.g.*, massive ice, interstitial ice, *etc.*). Finally, temperature measurements will be needed at the sample site to fully characterize the context in which the samples were collected.

To achieve these objectives, CaRI recommends that SMD/PSD invests in instrument development and concepts of operations for crew-based *in situ* characterization of volatile samples on the lunar surface. As examples, neutron spectroscopy has proven to be a valuable technique for identifying volumetric hydrogen (down to ~1 m depth). This technique would be ideally suited for reconnaissance and for selecting sampling site(s) to increase the probability that the precious cold stowage returned samples actually do contain lunar volatiles (instead of sampling a "dry spot" on the Moon). Prior to sampling, the volumetric water equivalent hydrogen (WEH) obtained from neutron measurements must be mapped at a human scale (not the 10s+ km resolution currently available from orbital measurements). Once a

subsurface sample (core, drive tube) is collected and sealed on the lunar surface, an adjacent subsurface sample can be collected for *in situ* characterization. As a baseline, the LCROSS mission utilized visible/near-infrared spectroscopy to identify the large variety of observed volatile compounds; therefore, this technique, using a hand-held spectrometer by a crew member, would be a viable option for *in situ* volatile composition and abundance measurements. Coupled with mm (or better) scale imagery of subsurface stratigraphy (downhole images and/or core imagery) and *in situ* measurements of temperature and lighting, this information is key for understanding alteration of the sample during stowage and transport as well as supporting terrestrial lab measurements. Multiple variables will ultimately affect the state and analysis of lunar volatiles back on Earth (*e.g.*, sample volume, stowage temperature, sample container size and headspace volume, abundance and type of volatiles present, regolith porosity, *etc*.). Due to these multiple unknowns, *in situ* characterization is required to ensure that the scientific integrity of the samples has been maintained; only then can scientists confidently characterize the origin and nature of lunar volatiles using the world's laboratories, both now and in the future.

7) Assess potential hazards associated with the desired samples and whether or not HEOMD should assume that all cold conditioned samples are hazardous.

Figure 1 shows the different "Grades" of PSRs, defined by increments of 20°C. The volatiles that could be present in different PSR Grades are based on sublimation temperatures for each volatile under lunar pressure (10^{-15} bar based on Apollo measurements). As described above, the colder a PSR, the more volatile species it is capable of containing. The most hazardous volatiles, based on NFPA ratings, OSHA allowable exposure limits, and NASA Spacecraft Maximum Allowable Concentrations (SMAC) include H_2S, SO_2, CO, HCN, and NH_3. However, other volatiles such as CH_4 may be hazardous to humans as well. These volatiles are modeled to appear in PSRs of Grade 4 and below (100 K / -173°C or lower temperatures). However, PSRs warmer than 100 K (-173°C) may still contain compounds such as methanol (CH_3OH) that are dangerous at high concentrations. We recommend referring to the latest SMAC released by the NASA Toxicology Office to assess the relative hazards of the various compounds.

Here we consider H_2S to be the most hazardous of the volatiles measured by LCROSS, and recent calculations by the JSC Toxicology group set 5 ppm as the upper allowable limit for crew exposure for one hour in flight and 0.7 ppm as the upper limit for a seven-day period. Based on these values, 63 mg is the maximum mass of H_2S that could safely be released into the Orion cabin (approximate internal volume estimated 9 m^3) for one hour, or 9 mg for one week. At the levels measured by LCROSS (16% H_2S relative to water, total volatile abundance 5 wt.%), this means the maximum sample mass that could be exposed to the cabin is 8.4 g for one hour, or 1.2 g for one week, assuming the sample is from a Cabeus-like PSR. However, scientific integrity of volatile samples is optimized by minimal loss of volatiles from the sample container, and thus robust sample containment is of critical importance for both preserving the scientific integrity of these samples as well as ensuring crew health and safety. Therefore, we recommend redundant, H_2S-compatible seals and sample containers for all volatile samples so the entire necessary mass of sample can be returned safely.

Summary and Recommendations:

1. Sample return at -80°C will enable an initial assessment of the range and abundance of volatile compounds that may be present in samples from special regions (shadowed or cold trapped) at the lunar south pole. However, we recommend that the Cold Stowage team evaluate the feasibility of a -85°C freezer to avoid the triple point of H_2S in flight. Future evaluations by the CaRI team will refine the recommended flight stowage temperatures for the samples from cold regions.
2. Many Artemis science objectives related to volatiles science will require sampling material from multiple locations and depths, including material that has been much colder than -80°C for potentially billions of years. To complete these sample return objectives, systems to visit, extract samples, transport, and curate these samples at cryogenic temperatures (-200°C or lower) must be developed.
3. There is a complex science interaction between volatile sample composition, form, abundance, stratigraphy, and age that directly affects recommendations for storage temperature, container size and form, and curation requirements. Additional laboratory studies and modeling are required to fully understand and quantify these effects.
4. CaRI recommends that the Cold Stowage team continues to communicate with scientists and include scientific expertise in Design Reviews and functional tests to help identify and communicate any issues regarding the stowage requirements and final designs.
5. CaRI recommends that SMD invest in instrument development and concepts of operations for crew-based *in situ* characterization of volatile samples on the lunar surface. *In situ* characterization is required to identify optimal locations for volatile sampling, characterize samples to understand volatile losses and alterations during sample transport and stowage, and to complement scientific analyses in terrestrial laboratories.

Future Work:

No.	Task	Need Date
1	Modeling estimates of wider range of volatile compounds than LCROSS	Nov. 2021
2	Laboratory storage testing of moderate-fidelity volatile simulants at ambient, -20°C, -80°C, and cryogenic (liquid nitrogen) temperatures for 1-2 weeks to simulate flight conditions	Nov. 2021
3	Laboratory storage testing of high-fidelity simulants for weeks to months to simulate flight and ground/curatorial processing	2022 –2024 (AIII samples) 2024 – 2027 (AIV + sustainable samples)
4	*In situ* instruments to support cold sample return (*e.g.,* thermal heat probe, hand-held visible/near-infrared spectrometer, crew deployable neutron spectrometer) ready for flight	Artemis III Payload Stow Data (est. Nov. 2024)

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Attachments:

Gerakines et al. (2020) Volatile Sample Return by Artemis III. White Paper submitted to the Artemis Science Definition Team.

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Date of Request: 6/30/2021, presented to CaRI 8/2/2021
CaRI Adjudication Leads: Kelsey Young and Caleb Fassett

Background: An AES working group has been convened to define a set of science and calibration requirements for a Crew Handheld Camera. Because this camera would fly on Artemis missions, the AES working group also needs to determine the Camera's ConOps for Science use cases during Artemis Extravehicular Activities (EVAs). The current plan is that the Handheld Camera will be certified for used on Orion, Gateway, HLS, and during lunar surface EVAs. The primary purposes for the camera will be documenting mission milestones with still and video imagery, providing live video for crew interviews with the media, and providing public interest imagery. The camera could also have scientific utility, including documenting sample collection, regions of geologic interest, and other EVA activities. For example, the Artemis III SDT report recommendation 6.3.7-1a stated that "NASA should ensure that in-situ imaging capability is available to crews during EVA to document exploration, sampling, and instrument deployment."

The request to CaRI was to (a) identify science requirements for EVA utility of the Handheld Camera, including for its calibration, and (b) to determine whether any science requirements exist that are beyond the scope of the current Handheld Camera development plans.

Request: The Handheld Camera team presented the following questions to CaRI:

1. What science requirements are there for the crew Handheld Camera (resolution, lens selection, metadata, accessories, augmented lighting, dynamic range, spectrum, etc)?
2. What science requirements exist for the calibration of the Handheld Camera during an EVA? What specific colors are needed for calibration purposes? From what distance should the Sample Marker be photographed during an EVA? Are there any surface properties that must be met (i.e. reflectivity)? Are there any other requirements the Sample Marker must meet to support photography on the lunar surface?
3. What, if any, any science requirements exist that are beyond the scope of the current Handheld Camera development plans?

***Introduction*:**

Detailed scientific objectives for Artemis missions that would be best achieved by imaging have not yet been defined. Typically, this would occur prior to defining measurement and instrument performance requirements for science. As a result, CaRI has worked to identify some of the probable scientific use cases (Table 1) for imaging based on discussions within CaRI, as well as with other scientists within NASA and in the broader scientific community and the outlined science objectives from the Artemis III Science Definition Team (SDT) Report. There are likely other scientific use cases for surface imaging that are not identified in Table 1, but by engaging many stakeholders in developing this response, we have attempted to capture the most important measurements and any associated camera and calibration requirements. These use cases also focus on how imaging can help support the objectives prioritized in the Artemis III SDT report, including the documentation of samples and sample sites before, during, and after sample collection. Context imaging for sample acquisition is a threshold (science floor) measurement for any Artemis mission. Questions related to regolith structure and imaging for 3D photogrammetric purposes are worthwhile targets for analysis but require more rigorous requirements and are a reach goal for imaging.

Some of what was asked of CaRI for imaging requirements needs to be left wholly or partially for future trades. Lens selection is a good example: CaRI currently does not have enough information on the site-specific science requirements to provide a recommendation for a preferred lens or lenses. For practical reasons, the context imaging use cases and regolith imaging use cases in Table 1 may lead down separate paths, where two desirable measurements would result in different choices for lenses (wide- vs. narrow-angle views) as well as for imaging ConOps. If two Handheld Cameras are available to the crew on one mission, one way of reconciling these differences would be having different lenses on each of the two cameras during one EVA. Alternatively, switching lenses during an EVA might be considered, although the feasibility and challenges of doing so should be carefully examined (for example, mitigating the challenging lunar dust environment). We recommend that lens(es) are selected that address all requirements and use cases in Table 1, even if that means two cameras or two (or more) lenses. Similarly, we provide initial recommendations on calibration standards, but without further definition of science objectives, ConOps, and camera characteristics, it is impossible to make fully informed recommendations related to these standards.

From CaRI's perspective, the precedent from Apollo for photographic documentation of landing sites should be the minimum threshold for what should be accomplished with Artemis. The revolution in digital cameras subsequent to Apollo should transform both mission documentation for analysis after flight, as well as how the real-time science backroom – and general public – experience Artemis exploration. Apollo had very limited real-time imagery aside from TV camera footage which limited the capability for real-time science support during EVAs. Imaging is central to that real-time science support capability, as has been demonstrated in planetary analog mission simulations (e.g., Hurtado et al., 2013; Young et al., 2013). The aim is to improve imaging for situational awareness to improve the quality of strategic support that a science backroom can provide.

Science Goal	Science Objective	Measurement/Operational Requirements	CaRI Suitability estimate for Handheld Camera	ConOps/Hardware/Measurement Notes
1. Geologic Context and Context Imaging	**a. Context for acquired samples, including rocks, regolith, and volatile sampling (including in shadow and full darkness).**	**Before & after imaging of Samples. Sample orientation and location.** **Illumination sufficient to document sample collection in shadow.** *Resolution needs to be sufficient to see samples tools will select for.* Threshold: 1mm/px at 1 m standoff (Goal: 200 microns/px at 1m standoff)	H	Illumination at the South Pole will be a challenge compared to Apollo. HDR imaging may help. Low-noise detectors will help. Image stabilization hardware may also help. Crew will be expected to image sampling targets both before and after sampling, with Sample Marker in view.
	b. Context for other science instrument measurements and instrument deployment	**Before & after imaging of deployment.** *Resolution needs to be sufficient to see relevant hardware + targets for other science instruments.* 1mm/px at 1 m standoff. (Goal: 200 microns/px at 1m standoff)	H/M	It is desirable to monitor instrument deployment with continuity (see 3b); for this reason, it may be preferable to have this done with remote, rather than handheld, imaging.
	c. Context color	**Color imaging.** *Low Sun, so processed color on the ground might detect color differences better than crew.*	H/M	Overall expectation should be for very little discernable/usable color variation at the extreme incidence angles near the poles, so postprocessing on the ground will be necessary.
	d. Multispectral capability (for mineralogy and optical maturity)	**Multispectral imaging.** *Preferred bands TBD; depend on detailed objectives.*	L/M	Desire for ~7 bands from UV to IR; could use a series of LEDs at specific wavelengths, or interchangable filters. Reflectance will also require calibration imaging.
	e. 3D characterization of terrain (natural and modified, e.g. trenches) and objects.	**3D point-cloud derivation from images** 1 cm/px DEM with 0.5 cm precision at 1 m standoff	M	Techniques to consider (1) stereo photogrammetry; (2) Structure from Motion; (3) Structured light. SfM and/or stereo imaging require specific ConOps. Structured light requires separate hardware. Non-imaging approaches exist (lidar). Geometric calibration imaging will help with (1) or (2). A mast could extend the perspective of images.
2. Regolith characterization and fine structure	**a. Geotechnical assessment of regolith; other interaction of hardware with regolith.**	**Resolve bootprints; imprint of lander legs; Plume Surface Interaction (PSI) effects; etc.** 1-2 mm/px resolution at 1 m standoff (finer resolution will narrow uncertainties for some goals)	H	May require ConOps to capture multiple images of regolith targets from different angles, at different lighting conditions, etc.
	b. Regolith size-frequency distribution, grain shapes. Imaging phenocrysts and texture of larger rocks.	**Resolving grains (~median grain size; 80-100microns); need 3-5 pixels/grain.** Goal resolution: 10-20microns/pixel Threshold resolution: 50-100 microns/pixel	M	(1) may need a specific lens to achieve necessary resolution; (2) may require a camera mounted close to the surface (challenging in suit) or could bring regolith into a tray from scoop or core.
	c. Grain-scale color, mineralogy, and optical maturity data	**Resolution of individual grains** (see 2b, above), and **multispectral capability** (see 1c, above).	L/M	
	d. Structure of undisturbed regolith	**Same as 2b, but cannot disturb regolith (or scoop it) before in situ measurement.**	L/M	Need to be away from plume-disturbed zone near lander.
3. Real-time & exploration science	**a. Backroom support of sample selection.**	**Rapid comm of data to ground.**	H	Compressed images are preferable to downsampled images if bandwidth-limited.
	b. Tracking and reconstruction of EVA activities.	**3rd Person POV (e.g. tripod or lander mounted camera).** Could be ground-controlled or autonomously track crew (e.g. with a motion-tracking mount). May support 1b.	L	Ideally get as much end-to-end capture of EVA activities as possible. Would be challenging to achieve with just a Handheld Camera because of required crew attention. Some of this objective may be captured by suit or lander cameras.

Table 1. Anticipated Scientific Use Cases for Artemis Imaging.
Suitability Assessment for Handheld Camera: H: Suitable; clearly can fulfill objective M: Possibly suitable (specific ConOps/hardware trades required) L: Limited suitability (alternatives preferred).

1. What science requirements are there for the crew Handheld Camera (resolution, lens selection, metadata, accessories, augmented lighting, dynamic range, spectrum, etc)?

Resolution: From Table 1: A requirement of 1 mm/px from a distance of 1 m (with a goal of 200 microns/px at 1 m standoff) would meet many science context objectives. Resolving regolith grains requires a 1-2 order of magnitude improvement (goal: 10-20 microns/pixel, threshold resolution: 50-100 microns/pixel). Increased resolution may be accomplished by the crew getting closer to targets where possible, though this may be challenging given suit mobility constraints. The assumption for the operations of the camera is that the crew will take photos approximately 1 meter from the target (or the approximate waist-to-chest level of a suited astronaut).

Lens Selection: Requirements to inform this selection are in Table 1; see also Introduction, above.

Metadata: See Specific Recommendation I-A, below.

Accessories: From Table 1, some accessories are worth considering that would provide the Science Team with additional information with which to interpret surface activities – both real-time and during post-mission analysis. Specifically, (a) different filters or narrow-band illumination modes for color or multispectral imaging to assess mineralogical and maturity variations, (b) augmenting a camera with structured light capability, (c) remote mounting / remote operation capability.

Augmented Lighting: From Table 1, the science requirement is to sufficiently augment lighting that it is possible to resolve features in full shadow, including areas of shadow where natural scattered light may be minimal (e.g. Permanently Shadowed Regions (PSRs), including micro-PSRs (see Hayne et al., 2021). In PSRs, augmented lighting ideally should also be designed to minimally alter the surface thermal environment, and any alteration that lighting might trigger needs to be modeled and understood. Augmented lighting for other crew activities is likely sufficient to meet this requirement, though it is presently being carried as a system-level risk.

Dynamic Range: High-dynamic-range (HDR) imaging and storage of images at higher bit depth may be worthwhile to adequately resolve both areas in direct illumination and shadow (pending testing in analog illumination environments). Along with HDR, low-noise sensors should be prioritized, particularly given the challenges of imaging in partial illumination and partial shadow that will frequently arise in the polar environment.

Spectrum: With the low Sun and resulting extreme lighting environment, natural color variations will be very hard to discern on the Moon. Color or multispectral data from a camera may thus reveal color differences invisible to crew. Using filters or illumination for this purpose may require removing "hot mirror" or Bayer filter mosaics that are part of the default design.

Additional Specific Recommendations Related to Camera Requirements and ConOps:

I-A. Recommendation: To maximize science return from the Crew Handheld Camera, relevant metadata should be captured about each image (clock/mission elapsed time, exposure, focal length, aperture, inertial measurement unit for orientation, sensor temperature, etc.). Image timing is particularly important to help tie photographs to other measurements and data streams related to EVAs. Other metadata such as image acquisition location is desirable, but a lack of this

information can be mitigated either by frequent imaging of landmarks and/or careful tracking of image timing and EVA progress.

I-B. Recommendation: The Moon is a dusty environment, but the Apollo Hasselblad experience demonstrates that high-quality scientific imaging can be obtained from astronaut-controlled images without being overwhelmed by dust. We understand that a key reason was that the Hasselblad focused beyond the dust accumulating on the lens. **We recommend that the Handheld Camera be designed such that the focal plane is beyond the location of dust on the lens, providing a similar tolerance of dust accumulation as its Apollo predecessor.** Similar design constraints have been incorporated into cameras used on MSL and Mars 2020 for example (Maki et al., 2020).

I-C. Recommendation: The Handheld Camera's image storage memory should be capable of operating in the challenging environmental conditions of EVA with sufficient storage capacity to maximize image collection during a single EVA. Methods for backup of raw images (potentially by wifi to the lander) may be worth considering if they add resiliency to the system, e.g., if the camera needs to be left on the Moon.

I-D. Recommendation: The Handheld Camera's battery should be capable of operating for the full expected length of a single EVA, with some margin, to remain available for use throughout surface operations. Important scientific documentation could be lost if a camera becomes unavailable during EVA.

I-E. Recommendation: To the extent that bandwidth allows, making full resolution images available to a science backroom as soon as possible is desirable to maximize science return (see, e.g., Recommendation 6.3.7-1b of the Artemis III SDT Report). Compressed images (i.e. 8:1 compression) may be acceptable for this purpose to save bandwidth, particularly if it is possible to retain full resolution images on the camera for later retrieval. Raw lossless images can be stored and returned with the crew.

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2. What science requirements exist for the calibration of the Handheld Camera during an EVA? What specific colors are needed for calibration purposes? From what distance should the Sample Marker be photographed during an EVA? Are there any surface properties that must be met (i.e. reflectivity)? Are there any other requirements the Sample Marker must meet to support photography on the lunar surface?

Calibration during EVA: Camera calibration activity needs to start pre-flight (see II-A). During flight, regular imaging of a sample marker for color calibration (II-B) under different illumination conditions is desirable. A geometric calibration standard is needed but does not necessarily need to be imaged as frequently; at the beginning and end of EVAs is likely sufficient. The geometric standard thus could be placed on either the sample marker or mounted on other hardware.

Specific Colors for Calibration Purposes: See specific recommendation II-B, below. Note that we provide initial recommendations on calibration standards, but without further definition of

science objectives, ConOps, and camera characteristics, the specific science requirements for calibration targets remain preliminary.

Distance for Photographing Sample Marker: As long as the Sample Marker is resolvable and illuminated, it can be photographed from any distance. We recommend, in the science cases where Sample Markers need to be used (i.e. sampling, relevant science payload deployment), the crew takes at least one photo within ~1 meter of the target and at least one photo at a greater distance (> ~3 m) from the target. The Sample Marker should be resolvable at both distance ranges.

Surfaces properties that must be met: Generally covered by Table 1.

II-A. Recommendation: To maximize the science return, a handheld camera should be calibrated as a scientific instrument both radiometrically and geometrically, and tested rigorously under laboratory and analog field conditions. Example testing: optical and geometric calibration; testing of camera performance under illumination conditions analogous to those of the lunar south pole (i.e. at facilities that exist for this type of work at JSC and ARC); TVAC testing of camera performance, testing of dust tolerance, etc.

II-B. Recommendation: Reflectance, color, and geometric calibration standards should be developed on a tool or target that can be imaged in the lunar environment with the Handheld Camera on a frequent basis. A photometric standard with multiple calibrated reflectance levels in both grayscale (e.g., 0% [black], 10%, 20%, 30%, 60%, 100% [white]) and color (blue, green, yellow, red) would aid in scientific image interpretation. A print with geometric calibration (e.g., a checkerboard, with well-marked increments of known size, e.g. 1mm, 1 cm, etc.) may aid in assessing camera geometric behavior. The procedures for using these standards and deriving accurate imaging should be tested in the laboratory and field before deployment on the Moon.

II-C Recommendation: The crew should be trained to practice acquiring images with techniques optimized for science. For example, if the Handheld Camera is to be used for 3D landing site characterization, the photogrammetric and structure-from-motion techniques require images to be obtained with a sequence of carefully chosen positions with respect to targets and illumination. In addition, a specific sequence of images will be desired prior to sample collection, and that sequence should be practiced as well.

II-D Recommendation: The Sample Marker should include design features to enable science targeting and real-time science support. As the Sample Marker will often be used to provide scale and calibration for sampling targets and other scientific features of interest, the Sample Marker should include a technique for pointing/targeting to the sample or other scientific feature (i.e., a reconfigurable arrow, capable of operating in the lunar dust environment, that the crew will point at each target when the Sample Marker is deployed). Additionally, the series of Sample Markers on each mission should all have unique identifiers, to aid in both documentation and in real-time science support.

II-E Recommendation: The Artemis camera design, development, and operations teams would be well-served incorporating experience and lessons learned from the extensive experience science has gained using cameras on Mars rovers. Though the lunar and martian environment are not

identical, there are some shared challenges (including dust, lighting, thermal, and ConOps) that have been worked for two decades for science-driven observations.

3. What, if any, science requirements exist that are beyond the scope of the current Handheld Camera development plans?

The request for CaRI to consider science requirements for a Handheld Camera on the lunar surface early in the requirements design is to be commended. However, the science that would be obtainable from a multipurpose Handheld Camera would be somewhat different from what would be possible with a science camera designed and deployed primarily to achieve specific science objectives. **CaRI recommends that crew-deployed cameras be considered as science instruments solicited as part of future Artemis instrument and science payload calls, and/or to support exploration aims for maximizing the science value of EVAs.**

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Request #: CaRI 004
Requestor: Artemis Curation Team
POC: Julie Mitchell
Date of Request: August 10, 2021
CaRI Adjudication Leads: Jamie Elsila Cook and Juliane Gross

Background:
Sample collection and transport will expose the Artemis returned samples to various levels of contamination. An end-to-end sample Contamination Knowledge (CK) and Contamination Control (CC) Plan is needed to: 1) minimize sample contamination, 2) document/track contamination throughout the mission, and 3) ensure consistent adherence to sample contamination requirements throughout the mission. Currently, there is no Artemis program-level CK/CC plan. However, science inputs are needed to constrain contamination limits and aid in the development of engineering, operations, and facility requirements for contamination control and knowledge. CC and CK requirements will be referenced by the Curation Plan and engineering Contamination Control Plan.

Request:
The CaRI-004 request asked for sample science focused requirements for different types of contamination in the areas where they are needed for returned geologic samples, since these requirements are currently not established or codified in a mission-level CC/CK document. The initial request asked that these be provided in the form of outgassing limits, materials compatibility for sample intimate surfaces, what materials are allowed/disallowed in proximity to the samples, and/or allowable quantities such as "XX ng/cm^2," where XX is the compound/element of interest.

The request also asked that future documents for curation, engineering, and operations CC/CK be reviewed by the CaRI on an as-needed basis to ensure alignment with Artemis science priorities/goals, or that recommendations be given if the requestor should be referred to another group (e.g., ExMAG) for review of those documents.

Note: this request does not cover volatile contaminants, which will be the subject of a future request.

Analysis:

In conducting its analysis, the CaRI team notes that science requirements for all types of contamination knowledge and control are specific to the science question and analysis to be conducted on the returned samples. Although the Artemis III Science Definition Team (SDT) report provided general guidance on the types of sample science and returned sample analyses that would be expected, it is difficult or impossible to create specific requirements in the absence of prioritized sample science questions, as many elements in the periodic table at quantities from ppb to wt% are used in lunar science. Without defined science questions that drive sample requirements, CaRI can only provide initial estimates of acceptable contamination limits that will need to be revisited and refined as science questions are identified and prioritized.

We also note that many of the questions identified in the original CaRI-004 request address contamination engineering requirements (e.g., allowable ng/cm^2 of a particular species/element on a tool or spacecraft component). Such contamination engineering requirements must be derived from science requirements on the sample (e.g., allowable ng/g of particular species in the returned, curated sample(s)). The science requirements can define a contamination budget for the lifecycle of the sample, which must then be implemented across multiple teams within the mission. Thus, there are two areas addressed in our analysis and recommendations: 1) Defining contamination requirements, including science-based total contamination budgets for species of interest and considerations for how these budgets are related to engineering or implementation requirements, and 2) Providing insights into how these budgets can be managed.

1) Contamination Requirements:

There have been no widespread community concerns that sample analysis for inorganic elements and compounds has been hindered by the previous procedures used in collecting, preparing, and curating the Apollo samples. Thus, in general, the cleanliness protocols and requirements used for Apollo-era sample collection and curation of the Apollo samples appear to be sufficient to meet scientific needs and should serve as a minimum requirement. Documentation of these protocols can be found in references such as Flory and Simoneit (1972) and in the Lunar Receiving Laboratory Cleaning Procedures.

The current request includes contamination from tools and their materials along with overall mission-level cleanliness requirements. Input and recommendations regarding materials for tools has previously been provided via the CaRI-001 and CaRI-005 adjudication documents. Although particulates from tools are a potential source of contamination, Day et al. (2018) conducted a survey of lunar mare basalts and crustal rocks looking for contamination and found that metal contamination plays a negligible role in the compositional variability of the siderophile and trace metal compositions preserved in these samples. They calculated that significant (>0.01% by mass) addition of stainless steel would be required to strongly affect the composition of the HSE, W, Mo, Cr, or Cu for most samples.

As was also noted in the CaRI-001 team adjudication, sources of contamination are largely a concern on the exterior of samples. In all but the freshest lunar samples, billions of years of micrometeorite bombardment and solar wind impingement have “space weathered” the exterior surface. This weathering rind and its composition are of interest to scientists, but typically these studies are not affected by trace chemical contamination. The majority of lunar sample requests are for the interior of samples, meaning that limited amounts of surface contamination may be tolerated in preparing the samples for many analyses. In addition, “dilution cleaning,” or passing one or more “throwaway” samples (especially soil samples) through the sample transfer chain prior to delivery of the first actual samples of interest, as has been planned for Mars Sample Return (2014 Organic Contamination Panel), can be used to minimize contamination on sample-intimate surfaces prior to collection of samples of interest; this process should be planned carefully for Artemis to consider any sample mixing concerns.

As mentioned previously, science requirements can set a limit (measured in ng/g) on how much of a contaminating species can be present in the returned, curated sample before science measurements are adversely affected. The conversion of the ng/g science requirement to a ng/cm^2 surface cleanliness requirement is dependent on the total sample mass expected, the area of surfaces that may contaminate the sample, and an assumption of how efficiently surface contaminants are transferred to the sample. Attachment 1, "Cleaning Calculations.xlsx", demonstrates an example of this type of calculation, similar to that used by OSIRIS-REx (Dworkin et al., 2017); if such a calculation method were used, it would need to be refined as the contamination budget is distributed among different aspects of the Artemis mission.

For inorganic species, a cleanliness level and sample contamination budget that is at the very least equal to and ideally better than the Apollo-era levels is desired. Once science questions are prioritized, element-specific requirements need to be set; such requirements can be based on the known abundances in various lunar rock types. Attachment 2, "Inorganic Contamination Calculations.xlsx", demonstrates an example of this type of calculation for one element. If such a calculation method were used, it would need to be refined for all elements of interest and as the contamination budget is distributed among different aspects of the Artemis mission.

For organic contaminants, Apollo-era documentation and more recent analyses can be used to suggest science requirements. In particular, Flory and Simoneit (1972) states that during the Apollo era, "a contamination control plan was developed and implemented which eventually resulted in providing investigators with lunar samples containing less than 0.1 ppm total organic contamination." This suggests a limit of 100 ppb total organic carbon would be consistent with Apollo-era cleanliness. In addition, a specific requirement for amino acids could be created as a proxy for other contamination, as was done with the OSIRIS-REx mission (Dworkin et al., 2017). Recent analyses of hydrolyzable amino acids in Apollo 17 samples revealed concentrations of ~100 ppb in several soils (Elsila et al., 2015) with terrestrial biological contamination being the likely primary source, but with some probable contribution from extraterrestrial sources. A contamination target of 30% of this level would lead to a total amino acid limit of 30 ppb for the returned, curated sample. This target should be revisited when science questions are prioritized; if organic content is a high-priority science investigation, the contamination requirement may be lower or identify more compound-specific limits than this initial recommendation.

Verification of contamination levels, as well as understanding of any specific contaminant species, can be carried out through measurements on proxy witness plates and hardware coupons that have been cleaned with the same protocols as the sample-intimate tools (Dworkin et al., 2017). These coupons are important for contamination knowledge studies. Contamination knowledge witness materials can take a variety of forms (e.g., coupons from hardware production, wipes from hardware cleaning, removable/returnable witness coupons on flight tools, exposable/returnable zeolite or other simulant material, etc.), and the type of material and operational procedures required to sufficiently document the potential contamination depend on the science questions being prioritized. In particular, witness materials and procedures for volatile analysis require additional consideration and testing, as these have not been previously studied or flown.

2) Contamination Management

The science-based contamination budget (e.g., allowable ng/g of particular species in the returned, curated sample(s)) must be spread throughout all teams and processes involved in collecting, returning, and curating the samples (Figure 1). Typically for a sample-return mission, a Contamination Control Officer would be appointed who has authority over this budget and works with contamination, hardware, and spacecraft engineers and mission planners to determine how these requirements would be met to stay within the allowable contamination budget

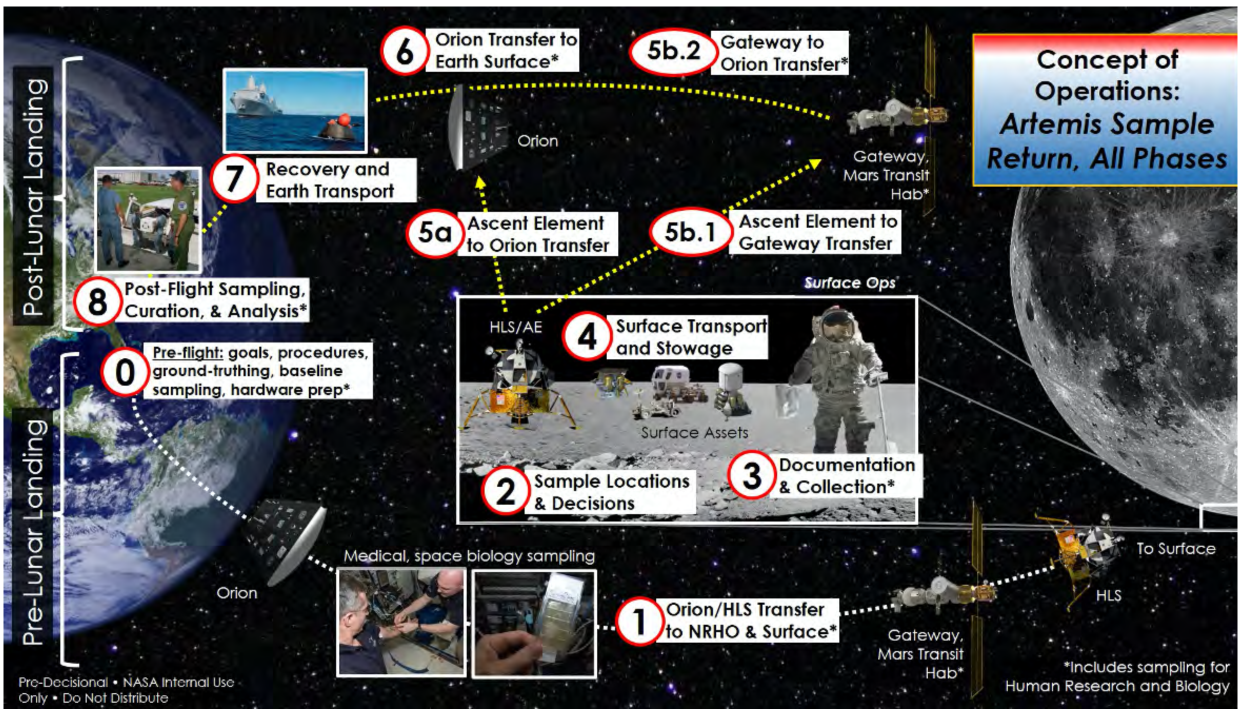

Figure 1: Multiple different teams will be involved in handling the Artemis samples. All teams must agree to a Contamination Knowledge and Contamination Control plan and be accountable for its execution.

In sample return missions, it has been the purposeful practice that the Contamination Control Officer should be separate from the Curation Officer. Curation's role is to implement requirements, not to develop or enforce them, and there is a potential conflict if one person is responsible for both the development and implementation of the contamination requirements. A "healthy tension" is required between curation and contamination control.

In previous missions (e.g., OSIRIS-REx), there has typically been a contamination control science lead who can address science that drives requirements, in addition to a contamination control engineer in charge of turning the science into implementable engineering requirements and overseeing that implementation. The OSIRIS-REx CC plan was overseen by Contamination Engineering, under Project Management/Systems Engineering, while the CK plan fell under the

Sample Analysis portion of the science side of the mission. Close collaboration between engineers and scientists was essential to the mission goal of returning a "pristine" sample with minimal contamination. As the OSIRIS-REx contamination team wrote, "Team communication was harder than expected – and it was already expected to be difficult," leading to the recommendation that "close communication among the science, engineering, and management stakeholders is the best path to understand what changes are possible and reasonable." Another key message was that "The process of developing and implementing contamination requirements cannot start too early in the mission planning process and must be maintained throughout implementation across the whole project. This require[s] authority behind the requirement..." (Dworkin et al., 2017).

Artemis is already facing decisions that need input from a contamination control working group containing engineers and scientists (e.g., Orion is working on their stowage plan, which includes sample stowage environments that will need to be considered in the overall contamination budget, e.g., the stowage of returned samples in proximity to crew food, trash, etc.). Any delays could lead to decisions that might not be compliant with later contamination requirements and might be difficult or impossible to change at a later point.

Recommendations:

1. In general, CaRI recommends that Artemis use Apollo-era cleanliness requirements and protocols as a minimum to minimize inorganic and organic contamination of samples, with the following specifics. However, CaRI strongly recommends that these requirements be revisited as Artemis science questions are prioritized. Note that the organic limits are the total allowable budget for the returned, curated samples, which means that these budgets must be spread across the entire chain of teams, tools, and environments that the samples are exposed to from collection to curation.
    a. Inorganic species: follow Apollo-era cleaning and curation protocols
    b. Organic species:
        i. Limit of 100 ppb total organic carbon contamination for the returned, curated sample.
        ii. Limit of 30 ppb total hydrolyzable amino acids in the returned, curated sample

2. CaRI recommends that hardware coupons of tool materials (previously addressed in CaRI-001) be cleaned with the same protocols and procedures as the flight hardware prior to being archived; these cleaned coupons will serve as contamination knowledge materials for the pre-flight cleaned tools. In addition to these coupons, CaRI recommends the use of empty sample bag(s) as witness materials that can be exposed to the same environment as the samples during collection and return. Additional considerations must be made for volatile contamination documentation (e.g., outgassing from suits, tool cleanliness, etc.), but these considerations require additional analysis and will have to be revisited in a future request. CaRI recommends ongoing discussions to be sure that future modifications to contamination knowledge requirements can be made as appropriate.

3. CaRI recommends that HQ-SMD work with HQ-ESDMD to make three assignments related to Contamination Control for Artemis samples:

    a. A mission-level Contamination Control (CC) Officer within ESDMD, who would be responsible for the full end-to-end contamination budget. We recommend that the CC Officer be an engineer working within ESDMD to ensure that this person has necessary expertise and authority for implementation of the CC plan.
    b. A mission-level Contamination Control (CC) Science Lead within SMD. The CC Science Lead would create and document the contamination requirements and contamination budget for the specific science questions identified by the Science Team. This individual should be outside of the Curation Office in order to preserve the healthy tension necessary between curation and contamination control. The Science Lead position could transition to a member of the Artemis Science Team upon appointment of that team.
    c. A Contamination Control Working Group (CC-WG) co-led by the CC Officer and the CC Science Lead, that would include representatives from all entities with environments or tools that would contribute to the contamination control budget. This WG would have the authority to generate documents such as a mission-level CC Plan, that would be implemented by the CC Officer. This paradigm could be similar to the successful Artemis Planetary Protection working group.

4. The CaRI board stands ready to review future documents for curation, engineering, and operations CC/CK on an as-needed basis to ensure alignment with Artemis science priorities/goals.

References:

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Dworkin J. P., Adelman L. A., Ajluni T., Andronikov A. V., Aponte J. C., Bartels A. E., Beshore E., Bierhaus E. B., Brucato J. R., Bryan B. H., Burton A. S., Callahan M. P., Castro-Wallace S. L., Clark B. C., Clemett S. J., Connolly H. C., Cutlip W. E., Daly S. M., Elliott V. E., Elsila J. E., Enos H. L., Everett D. F., Franchi I. A., Glavin D. P., Graham H. V., Hendershot J. E., Harris J. W., Hill S. L., Hildebrand A. R., Jayne G. O., Jenkens R. W., Johnson K. S., Kirsch J. S., Lauretta D. S., Lewis A. S., Loiacono J. J., Lorentson C. C., Marshall J. R., Martin M. G., Matthias L. L., McLain H. L., Messenger S. R., Mink R. G., Moore J. L., Nakamura-Messenger K., Nuth J. A., Owens C. V., Parish C. L., Perkins B. D., Pryzby M. S., Reigle C. A., Righter K., Rizk B., Russell J. F., Sandford S. A., Schepis J. P., Songer J., Sovinski M. F., Stahl S. E.,

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Flory, D. A. and Simoneit, B. R. (1972) Terrestrial contamination in Apollo lunar samples. Space Life Sciences 3, 457–468 (1972). DOI: 10.1007/BF00926775

Attachments:

1. Cleaning Calculations spreadsheet
2. Inorganic Contamination Calculations Spreadsheet
3. Lunar Receiving Laboratory Cleaning Procedures for Contamination Control (1971) Document # MSC 03243

Request #: CaRI 005
Requestor: xEVA Tools Team
POC: Adam Naids; adam.j.naids@nasa.gov; 610-731-1751
Date of Request: 7/21/21 and 7/23/21
CaRI Adjudication Leads: Juliane Gross

Background:

1) The xEVA Tools team requires approval for the use of materials needed to make softgoods items to support Artemis Geology Tool objectives on the lunar surface.
2) The xEVA Tools team requires approval for a number of miscellaneous processes used in machining and assembly for Artemis Geology Tools.

Both approvals are critical for the team to finalize their designs in order to meet Design Review milestones. The xEVA Tools Team understands that these decisions have implications for sample integrity and resulting science return. The EVA Team has a constant dialog with ARES scientists; they will be part of Design Reviews and functional tests. They will help the Tools Team identify and communicate any questions regarding the tools materials and final design. With approval of these processes the Tools team can start to finalize geology tool designs to meet Design Review Milestones.

Request:

1) The xEVA Tools Team wants CaRI to review traditional materials used to make EVA softgoods and ensure they are acceptable for Artemis. The following are a list of the softgoods materials being submitted for approval:
    - Chemglas 500F, Teflon Coated Fiberglass
    - Chemfab Standard CF214-1 BC
    - Teflon Film, Virgin PTFE skived film
    - Nomex Material
    - Ortho-Fabric, Style 116
    - Silicon RTV Rubber Sheet
    - Edgelock, GENTAL 101 (adhesive)
    - 966 Pressure Sensitive Adhesive Backing
    - Kevlar Thread
    - Aluminized Mylar, Reinforced

2) The xEVA Tools Team wants CaRI to review traditional manufacturing and assembly practices used in EVA hardware development and approve them for use on the lunar surface. The following are a list of the topics being submitted for approval:
    - Laser Part Marking
    - Chemical Conversion Coating with Alodine
    - Dry Film Lubricants
    - Glass Bead Blasting
    - Physical Vapor Deposition
    - Encasing and Protection Practices

Knowing that material and process selection can affect a contamination control plan, the xEVA Tools Team wants CaRI to provide input on these before they move forward with them for their flight hardware.

Analysis:

Contamination concerns arise when human activities cause a perturbation (usually an increase) in specific elements or compounds of interest to the analysis of those samples. Contamination components can be mixed into soil samples or transferred to particles and rocks; limiting these possible contamination occurrences as much as possible is important.

The primary concern with materials used directly in tools (sample intimate and non-sample intimate) and in processes for toolmaking is their potential to contaminate samples with trace metals and siderophile (iron-associated) elements. Siderophile elements and trace metals underpin a wide range of scientific inquiry but are frequently found at very low abundances (parts per billion), meaning that even small amounts of contamination can have large effects on their abundances. Day et al. (2018) conducted a survey of lunar mare basalts and crustal rocks looking for metal contamination and found that Apollo-era collection practices and current sample processing materials and procedures play a negligible role in the absolute abundance of the siderophile and trace metal compositions of these samples.

Macro-contaminants like fibers shed from suits and gloves, torn pieces of samples bags, etc. are readily identifiable and separable and have been found within soils collected during Apollo. The non-sample intimate softgoods materials listed by the xEVA Tools Team will not be in direct contact with the to-be-collected samples, hence contamination plays a minor role. Further, these softgoods materials have a long history of flight heritage for EVA items, were used during Apollo, and adhere to current NASA specifications (e.g., outgassing, etc.). No additional contamination due to these materials is known beyond what is outlined above. Collecting special samples in sealed containers will minimize contamination of the non-sample intimate softgoods materials.

Several concerns are noted for the traditional manufacturing and assembly practices used in EVA hardware development as listed below:

- *Laser Part Marking:* If tools can be cleaned to the appropriate cleanliness no major concerns would be noted.
- *Chemical Conversion Coating with Alodine:* This procedure adds chromium to the tool which could pose a contamination risk. However, if the surfaces are cleaned to the appropriate cleanliness standards, the contamination risk would be minimized.
- *Dry Film Lubricants:* Even though dry film lubricants normally do not migrate away from the contact surfaces they are applied to, MoS is a known contaminant for lunar samples, both for its main elements (Mo and S) and associated trace elements. MoS was prohibited for the Apollo samples and continues to be prohibited in the lunar curation facility for these reasons. Since the dry lubricants will be applied to parts of sample-intimate tools, the proposed dry film lubricants of MoS pose a major contamination risk. Samples contaminated with MoS (or other dry lubricants such as Zylan, or other Sulfide components) will have major consequences for scientific studies such as geochronology, siderophile-element studies, and organics. Alternatives such as Teflon would be acceptable and more appropriate.

- *Glass Bead Blasting*: As long as there is no melting and vapor depositing of the glass bead material (Na, Ca, Si) onto the blasted surface during the blasting process and the surface is cleaned to the appropriate cleanliness standard afterwards, contamination would be minimized and hence not a major concern. However, glass beads from the blasting process should be stored and kept as witness material.
- *Physical Vapor Deposition*: The main concern with Physical Vapor Deposition on sample bags is cleanliness of the interior (sample-intimate) surface of the bag. Vapor deposited aluminum or stainless steel can pose a contamination risk if particles are deposited on the inside of the bags that will come in direct contact with the samples. The ARES sample curators have found that cleaning the inside of bags to the appropriate standards is an extremely difficult process to implement and verify. They instead developed a process for sample bag marking that ensures the interior cleanliness of the bags by purchasing pre-cleaned Teflon bags (specifically, clean on the inside), heat-sealing the bags, marking the bag exteriors, cleaning the exterior of the bags after marking, and unsealing (cutting open) the bags afterwards for further use. If the xEVA Tools team develops their own process for keeping the bags (inside and outside) clean during the labeling process, or cleaned afterwards to the appropriate cleanliness standard, this process would pose limited contamination concerns.
- *Encasing and Protection Practices:* The request contained little information about the quantitative effectiveness of the proposed process in containing particles of dry lubricant. As noted above, there is a significant effect on samples of dry lubricants such as MoS, so the overall effectiveness of this process will need to be demonstrated before the CaRI team can assess the potential contamination risks of this process.

Recommendations:

1. CaRI approves the provided lists of softgoods materials for Category II (non-sample intimate) applications.

2. CaRI approves the Laser Part Making Chemical Conversion, Coating with Alodine, and Glass Bead Blasting practices if
   a) all tools can be cleaned afterwards to the appropriate cleanliness level in order to avoid or minimize contamination risks
   b) appropriate witness samples or coupons be collected and archived to enable their characterization if/when necessary.

3. CaRI does not approve the submitted Dry Film Lubricants, specifically MoS. CaRI recommends that Teflon be used as dry film lubricant instead.

4. CaRI approves the Physical Vapor Deposition process only if no vapor-deposited particles are on the inside of the bags. CaRI recommends that the xEVA Tools Team develop a similar procedure as outlined in the “Physical Vapor Deposition” Analysis above.

5. CaRI recommends that the xEVA Tools Team demonstrate the effectiveness of the proposed Encasing and Protection Practices process, including the level of particle and/or dry lubricant contaminants that could leak, for CaRI to reevaluate.

References:

CaRI 001 and attachments, detailing Apollo collection and curation materials and processes

Day, J. M. D., Maria-Benavides, J., McCubbin, F. M. and Zeigler, R. A. (2018), The potential for metal contamination during Apollo lunar sample curation. Meteoritics & Planetary Science 53, 1283-1291. DOI: 10.1111/maps.13074

Attachments:

CaRI Decision Package – Softgoods Materials_RevNC.pptx

CaRI Decision Package – Miscellaneous Machining and Assembly Topics_RevNC.pptx

Request #: CaRI 006
Requestor: xEVA Tools Team
POC: Adam Naids; adam.j.naids@nasa.gov; 610-731-1751
Date of Request: 10/18/2021
CaRI Adjudication Leads: Juliane Gross & Barbara Cohen

Background:
The xEVA Tools team requires approval for the use of 1) lubricants and 2) coatings for assembly of Artemis Geology Tools. Both approvals are critical for the team to finalize their designs in order to meet Design Review milestones. The xEVA Tools Team understands that these decisions have implications for sample integrity and resulting science return. The xEVA Team has a constant dialog with ARES scientists; they will be part of Design Reviews and functional tests. They will help the Tools Team identify and communicate any questions regarding the tool materials and final design. With approval of these lubricants and coatings the Tools team can start to finalize geology tool designs to meet Design Review Milestones.

Request:
1) The xEVA Tools Team wants CaRI to review lubricants for the Artemis Geology Tools. These lubricants are needed to ensure the proper work of sliding mechanisms where metal moves against metal. The following are a list of the lubricant materials being submitted for approval:
   - Krytox 240AC PTFE Grease
   - Braycote 601 EF Grease
   - Brayco 815Z Lubricating Fluid
2) The xEVA Tools Team wants CaRI to review coatings for components on Artemis Geology Tool assemblies including threaded inserts, rivets, faying surfaces, bearings, bushings, and threaded fasteners. Coatings are needed to protect the materials against dissimilar metals, corrosion and stress corrosion cracking. The following is the coating material being submitted for approval:
   - Super Koropon 515-700

Analysis: Dry Lubricants
Dry lubricants will be applied to parts of sample-intimate tools, and thus, can potentially pose major contamination risks. The previously proposed dry film lubricant of MoS_2 is not approved by CaRI as samples contaminated with MoS_2 (or other dry lubricants, such as Zylan, and those containing sulfides) would have major consequences for scientific studies such as geochronology, siderophile-element studies, and organics. The lubricants considered in this request are perfluorinated polyether (PFPE) based and some contain Polytetrafluoroethylene (PTFE = Teflon). Both PFPE and Teflon are allowed and used in the Lunar Curation facilities and are recommended for use in Artemis tool fabrication.

Krytox 240AC PTFE Grease: Krytox 240AC PTFE Grease is composed of a PFPE oil. The ideal temperature of this grease is between -34 to +288°C.

Braycote 601 EF Grease: Braycote 601 EF Grease is a mixture of small PTFE (=Teflon) particle and perfluorinated polyether liquid (PFPE). In addition to PTFE particle and PFPE liquid, Braycote 601EF also contains sodium nitrite as a corrosion preventative. The ideal temperature range for the Braycote 601 EF Grease is between -80°C to +204°C.

Brayco 815Z Lubricating Fluid: Brayco 815Z Lubricating Fluid is a mixture of small PTFE particles and a perfluorinated polyether-based (PFPE) fluid. Ideal Temperature range is between -72°C to above +204°C with up to 260°C for brief periods.

Advantages to PTFE/PFPE lubricants include:

- PTFE/PFPE have strong carbon-fluorine bonds, and thus, the PTFE/PFPE chain structure is extremely well protected and highly inert.
- PTFE/PFPE provides excellent high-temperature performance and makes these products extremely useful in the presence of highly reactive chemicals.
- PTFE has one of the lowest coefficients of friction of any solid.
- PFPEs are non-flammable and have low toxicity and low evaporation levels.
- PTFE/PFPE lubricants have similar useable temperature ranges between -34°C to -80°C and +204°C to +288°C

Other spacecraft sample return missions have also used PTFE/PFPE lubricants and provide additional guidance on their use, mobility, and potential for contamination of the samples.

Genesis: Braycote 601EF lubricant was used throughout the Genesis spacecraft. Although it is supposed to stay where it was initially deposited, it “traveled” to virtually all surfaces of the spacecraft, including the sample collector surfaces (Fig. 1). Outgassing of this lubricant led to formation of a thin (4 nm) film called “brown stain” (Calaway et al., 2007, Sestak et al., 2006, Allton et al., 2006), formed of polymerized C, O, Si, and F that was UV hardened to a chemically-resistant contaminant on the sun-facing surfaces (Burnett et al., 2005). Silicon targets have been cleaned of this material using UV-radiation-induced reactive atomic oxygen via ozone, a method unsuitable for natural geologic samples.

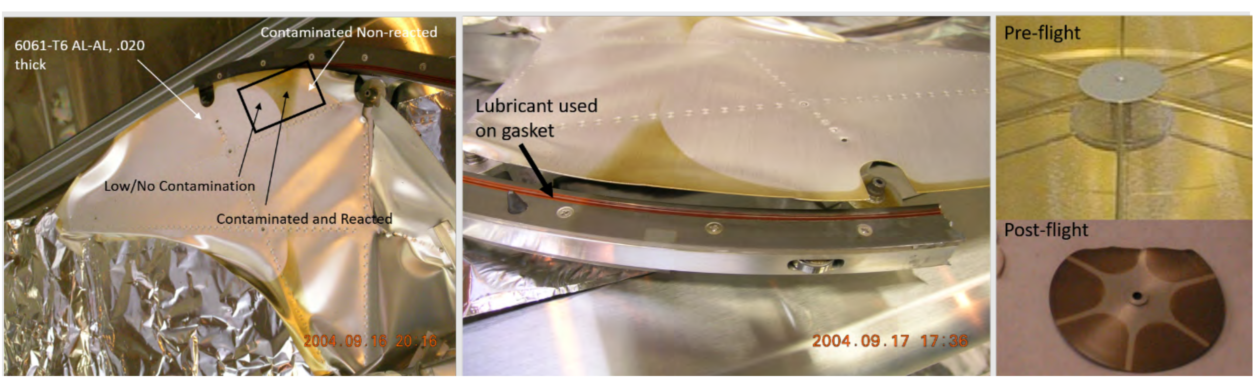

Figure 1. Examples of “brown stain” caused by lubricant polymerization on UV-exposed Genesis hardware.

OSIRIS-REx: Measurements of organic compounds are one of the main science goals of the OSIRIS-REx mission and accordingly, a detailed contamination control and contamination knowledge plan was created for the mission (Dworkin et al. 2018). The mission attempted to minimize the diversity of organic polymers (e.g., silicones, lubricants, adhesives) in sensitive areas of the spacecraft to reduce the complexity of any contamination and therefore simplify identification and interpretation of contaminants. The mission also attempted not to use lubricants near areas that would be subject to UV exposure. Small amounts of Braycote 601EF were used on the OSIRIS-REx spacecraft and on the TAGSAM wrist. Other lubricants and adhesives were used throughout the spacecraft. The OSIRIS-REx contamination knowledge archive of spacecraft materials is extensive and would be an excellent template to build upon for Artemis.

Mars 2020: The Mars 2020 lander and Perseverance rover contamination control requirements defined cleanliness zones based on a risk assessment of contamination on hardware in that zone reaching the sample as it is acquired and processed into a sealed, potentially returnable sample tube (Muller et al. 2020, White et al. 2017). Contamination limits for the samples include less than 1 viable Earth-sourced organism, less than 10 ppb (parts per billion) baseline (desired) or 40 ppb threshold (not to exceed) of total organic carbon, and limitations on a wide range of inorganic elements (Boeder and Soares, 2020). In the sample-intimate systems, Mars 2020 used PTFE directly on seal springs and on the sample drill bit and Braycote 601EF and Brayco 815Z in the adaptive caching assembly. Other lubricants and adhesives were used throughout the spacecraft. Samples of each lubricant are stored for contamination knowledge.

Analysis: Epoxy coating
Koropon 515-700 is a fluid-resistant epoxy coating that has a long history of being used in aviation as well as on the Space Shuttle and International Space Station. The Koropon 515-700 base component (Super Koropon) is composed of talc (≥20 - ≤50), butanone (≥20 - ≤42), n-butyl acetate (≥10 - ≤20), calcium chromate (≥1.0 - ≤5.0), titanium dioxide (≥1.0 - ≤5.0), and crystalline silica (<1.0).

Microanalysis of aged Super Koropon primer indicated a significant decrease in corrosion protection, as the primer turned rough and flaky and had significant chromium ripening (Fig. 2; Lomness and Calle 2006, Russell 2014). Though this epoxy sample was only inspected after 30 years of use, so it is unknown how long it took to age, it does show a mode for how Koropon may present as a contamination challenge (flaking). If flaking is the dominant mode, it may be relatively easily identified, isolated and removed from samples (see CaRI 001, fiber example). However, the organic components of Koropon (butanone and n-butyl acetate) are likely to have outgassing properties that may negatively affect samples much more rapidly. One study shows that Koropon epoxy yellowed (presumably due to polymerization, see *Genesis* example above) and offgassed multiple short-chain organic fragments during UV irradiation (Choate et al., 1969). Understanding the offgassing and mobility behavior of Koropon epoxy is critical to evaluating its suitability as a sample tool material. Because the xEVA teams have haven't offered any alternatives for Koropon, CaRI has to recommend that additional investigation of this material be conducted before adopting it for use in sample tools.

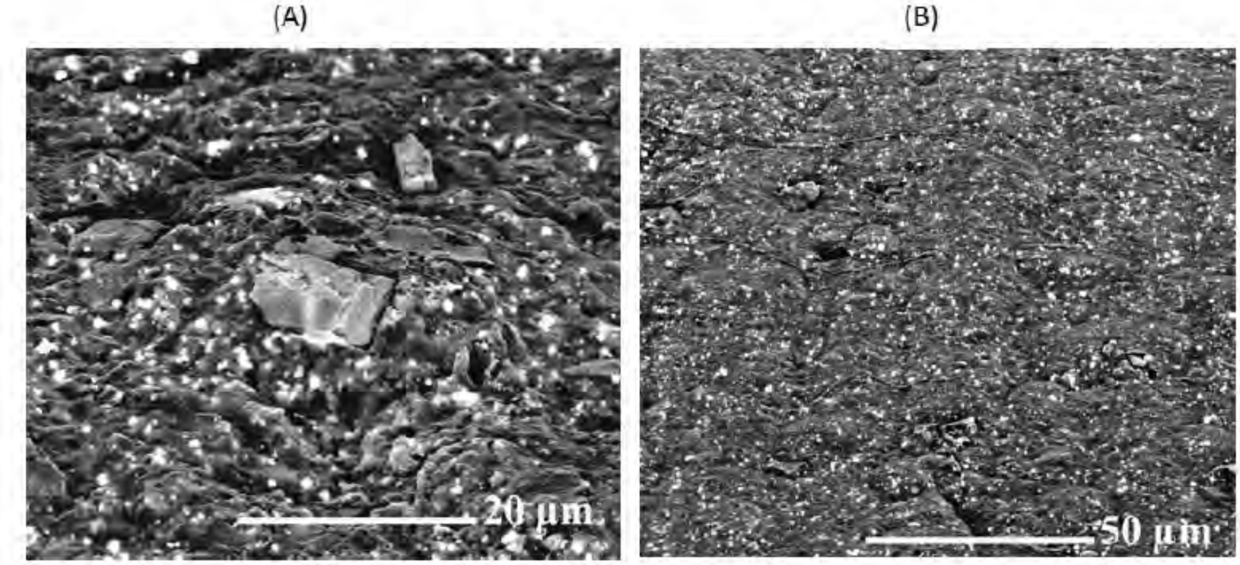

Figure 2. Backscattered electron images of Koropon primer from the space shuttle (A) and newly deposited coating (B) show the flaking behavior of older Koropon coatings.

In previous requests related to Artemis tools materials, CaRI has shown that using the Apollo curation materials and processes is sufficient to enable hard rock (i.e., non-organic/non-volatile) sample science with minimal contamination concern. However, the CaRI team has additional considerations for lubricant use in Artemis tools that should be considered as part of a total Contamination Control plan. Lubricant outgassing, mobility, and UV interaction could be a significant concern for Artemis tools. However, not using lubricants and coatings can result in more extensive shedding of particles from grinding together of dissimilar parts. The particle shedding could represent a worse contamination issue than lubricant contamination depending on science goals – e.g., HSE concentration will be affected by metal particles but not by lubricant. The decision to use coatings and lubricants on tools that may be disassembled and reassembled could also be a factor - removing nuts/bolts etc. multiple times may encourage shedding and creeping of the coatings.

An additional concern not previously realized on Apollo missions is the use of lubricants and coatings on tools likely to be used at the lower temperatures that are expected in the South Pole region. These temperatures may be lower than the minimum operable temperature specified for the approved lubricants. If the lubricants freeze and shed, particulate contamination of "frozen" lubricants and potentially also metal (since not lubricated correctly anymore) may be likely. Such particles, when brought back to room temperature, may not be physically separable in the same way fibers are. Furthermore, as noted in previous CaRI requests, a contamination budget for volatile samples has not yet been set, so we have not taken that into consideration in this analysis.

Recommendations:

- **The CaRI team recommends PFTE-based lubricants for Artemis tools, based on their long history of use in Apollo curation and other spacecraft.**
- **We recommend minimizing the diversity of potentially contaminating materials.** Braycote 601 EF Grease was used for O-REx and Genesis, and it has the lowest temperature range of -80°C and may be the best choice to be widely used.
- **The xEVA tools team must consider lubricants, and all materials, as part of an integrated Contamination Control and Contamination Knowledge (CC/CK) plan.** Samples of each lubricant that is used should be analyzed and/or archived for later analysis.
- **CaRI does not have sufficient information on the mobility and offgassing properties of Super Koropon 515-700 to recommend or prohibit its use.** We recommend additional analysis or research into its properties. As the request notes, if Koropon is disallowed, a Material Usage Agreement (MUA) will need to be written and signed by the Structural Engineering Division at JSC.

Acknowledgements: We thank Judy Allton, Nicole Lunning, and Andrea Harrington for information about how other spacecraft have used lubricants.

References:

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Boeder, P. A. and Soares, C. E. (2020) Mars 2020: mission, science objectives and build, Proc. SPIE 11489, 1148903. https://doi.org/10.1117/12.2569650

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Calaway, M. J., Burnett, D. S., Rodriguez, M. C., Sestak, S., Allton, J. H., and Stansbery, E. (2007) Decontamination of Genesis array materials by UV ozone cleaning. *38th Lunar Planet. Sci. Conf.*, Houston, USA. #1627. https://www.lpi.usra.edu/meetings/lpsc2007/pdf/1627.pdf

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Dworkin, J.P. et al. (2018) OSIRIS-REx Contamination Control Strategy and Implementation. Space Sci Rev 214, 19. https://doi.org/10.1007/s11214-017-0439-4

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White, L. et al. (2017) Organic and inorganic contamination control approaches for return sample investigation on Mars 2020, in Proceedings of the 2017 IEEE Aerospace Conference, Big Sky, MT, 2017. https://ieeexplore.ieee.org/document/7943709

Attachments:

CaRI Decision Package – Lubricants and Koropon_RevNC.pptx
CaRI 006 Attachment 1: Requirements for Materials in Building 31N
CaRI 006 Attachment 2: Materials analyses for Building 31N

Request #: CaRI 008
Requestor: xEVA Tools Team
POC: Heather Bergman; heather.r.bergman, 713-244-4694
Date of Request: 12/16/2021
CaRI Adjudication Leads: Barbara Cohen

Background:
The xEVA Artemis Tools Team is requesting CaRI guidance on the Artemis III sample and correlated sampling tools based on the Artemis III SDT to aid in the conversation with HLS, Gateway, and Orion to ensure that proper volume and mass are allocated for sample return on Artemis III.

Request:

- Clarification on the SDT report recommendations
- Guidance on highest priority samples/sampling and containment tools
- With these clarifications and prioritizations, the tools team will be able to create notional tool container designs and ensure there are available stowage locations on Orion for sample return.

Analysis:
The Artemis III Science Definition Team (SDT) Report was released in December of 2020. The SDT report includes a candidate science program that attempted to capture the highest-priority science for Artemis III (as defined in community documents) and provide the greatest feed-forward to follow-on missions and the build-up to the Artemis Base Camp. The SDT recognized that because the Artemis landing site and operations plan were still nascent, and that a competed Science Team for Artemis III was being planned, that a candidate science program was needed to scope design reference capabilities and needs. However, the SDT report also makes clear that trades and modifications to the candidate science program will need to be made as the Artemis III mission plans and the Artemis program mature.

Sample collection and return is an important component of the Artemis III candidate science program. Section 6.1 outlined the sample science and types of samples that the team envisioned as general needs. The candidate sample program that the SDT defined to meet the general science needs appears as Table 2.

Sample	Type	$Mass_i$ (kg)	N	Mass (kg)	N_{min}	$Mass_{min}$ (kg)	Investigations
Contingency	bulk	1	2	2	1	1	
Small clast	rake	1	4	4	1	1	1a-1, 1a-2, 1a-3, 1b-1 ,1b-2, 1b-3
Large clast	hand	1	15	15	4	4	1a-1, 1a-2, 1a-3, 1b-1 ,1b-2, 1b-3
Sealed core	drill	4.5	8	36	4	18	1f-1, 2a-6, 2b-1, 2c-1, 2c-3
Sealed surface	bulk	1	20	24	0	0	2b-1, 2c-1
Regolith surface	CSSD	0.5	4	2	2	1	1f-1, 2b-1, 2c-1
				Total 79		Total 25	

Table 2: Sample masses itemized by sample type, for two candidate programs, listed with the investigations that they would enable. Column labeled $Mass_i$ is the approximate mass per sample for each sample type. N and N_{min} are the number of samples for the nominal and minimum sampling programs, with Mass and $Mass_{min}$ listing the corresponding mass for N or N_{min} samples of each type.

The quantities and mass estimates in Table 2 were made under severe restrictions on the EVA distance that could be covered, the number of EVA excursions, the anticipated downmass to the Moon for payload delivery (including sample collection tools and containers) and upmass from the Moon for sample return. These constraints are enumerated on Page 6-3 of the SDT Report as follows:

1. The HLS shall deliver, at a minimum, 100 kg of scientific payload to the lunar surface. Of this, 20 kg are allocated for the sample return containers, 10-20 kg are allocated for cameras or other sensors to be used in the habitable environment, and 60-70 kg are allocated for tools and instruments to be used or deployed by astronauts on the surface (HLS, 2019).
2. The HLS shall return a minimum of 35 kg (or a goal of 100 kg) of scientific payloads (e.g., samples, inclusive of tare) to lunar orbit for return to Earth (HLS, 2019). Tare is expected to consume 9 kg of the upmass allocation in the minimum case, and 20 kg in the goal case.
3. The HLS shall be capable of operating on the lunar surface for a minimum of 6.5 Earth days (HLS, 2019).
4. The HLS shall be capable of supporting at least two (threshold) and five
5. (goal) surface EVA excursions per sortie. Nominal EVA excursion is 6 ± 2 hours; the lower end of that duration (4 hours) is the requirement for Artemis III (HLS, 2019).
6. The xEVA suit supports a walk-back capability of 2 km (xEVA, 2020).

The sample types in Table 2 were chosen to represent a range of samples that might be desired for return under the architecture constraints. The SDT recognized the role of the competed science team in further refining the science objectives for the specific Artemis III mission at the specific landing site, which would likely result in changes to the sample collection plan, including changes to the number and type of each sample. For example, a team may desire fewer sealed surface samples and more rake samples, depending on the nature of the geologic investigations planned for the site.

The SDT report makes clear in several locations that the architecture assumptions are extremely limiting and in particular, are inadequate for sample return. Finding 6.1.4-2 states unequivocally, "The high-priority Investigations described in this report require the collection of a diverse set of sample types, collected from geographically diverse locations broadly representative of the complex geology of the south polar region, and a total return sample mass from the Artemis III south polar site exceeding the average return mass for the Apollo missions." A recommendation and justification for sample return mass in the hundreds of kg was made by CAPTEM in 2002 for the Constellation program (CAPTEM report) and further developed in a white paper submitted to the UGIG (Lawrence and Mitchell 2022).

Nonetheless, the SDT report created two candidate sample programs within the upmass limitations given by the Artemis III HLS to enable creation of design reference scenarios of the type requested in this analysis. In this exercise, the SDT made the assumptions contained in Architecture point 2 above: the nominal case (100 kg total) would include 80 kg of sample and 20 kg of containment (tare), and the minimum case (35 kg total) would include 26 kg of sample and 9 kg of containment (tare). That is how the sample type and mass distributions were created and discussed.

The xEVA Artemis Tools Team reviewed the SDT document Table 2 and matched the nominal sample collection plan to requirements for the tools required to collect the samples and the containment and stowage needs. They then estimated mass, dimensions/volume and other needs for the hardware to enable the sample collection program. These quantities form a design reference that can be used for help ensure that sufficient requirements are being carried for tool design, upmass and downmass, and available vehicle volume shapes.

The xEVA Artemis Tools Team summed the returned sample mass and the sample containment estimates to calculate a total returned mass required for the nominal and minimum SDT programs. The calculated returned mass exceeds the allocations assumed in the SDT report, principally because the assumptions for the tare mass were off from what the xEVA team is actually developing. While tool designs are still in their early stages, the first look the tools needed shows that the mass needed to deliver them exceeds the 100 kg limit and this does not include any science payloads, a camera, or other things that that must be included in this allocation. In addition to the total mass limitation, Orion does not have the room to bring home a Secondary Sealed Container large enough to return all the samples in the nominal program. The current notional container (Fig. 1) is sized to fit 6 single drive tubes, 12 bulk samples, or a combination of the two.

Because of the fixed number and size of the transport liner, softgoods bags, and secondary containers for volatile samples, estimates for the tool and containment masses for the minimum program take up a larger fractional share of the returned mass. This highlights the Artemis III SDT Recommendation 6.1.4-4: *NASA should focus on the development of lightweight, double-sealed vacuum containers to return volatile bearing lunar samples to Earth. Minimizing the mass penalty for vacuum-sealing any given sample results in increased scientific yield of the mission since more mass can be allocated to the lunar samples instead of the sampling hardware.*

After the CaRI team received the xEVA Artemis Tools Team request and analysis, the UCIG requested that SMD document the most current estimates of mass and volume for samples, sample containers, and cold stowage. This mass estimate has been captured in several agency-level documents and will continue to be updated in those documents as mission plans and designs mature. These documents include:

- SMD exercise on Artemis Sample Return Enveloping Requirements
- HEOMD-413 - Utilization Sample Return Conditioned Transportation Needs for Artemis Capabilities
- HEOMD-416 – Utilization Delivery and Return Needs for Artemis Human Mission Capabilities

While these documents contain estimates of types/quantities of samples for various mission scenarios, those estimates are for planning purposes only. The final selection of specific samples to be collected for each Artemis mission will be determined by the Artemis Science Team and driven by the specific science goals for that mission and its landing site. Therefore, the estimates in the above documents should not be used to set requirements for numbers/types of containers for each mission.

Recommendations:

- **The CaRI team clarifies that the returned sample collection in the AIII SDT Table 2 is not the required sample return program for Artemis III.** The SDT report designed a candidate program to enable early design reference capabilities. It is expected that the competed science team will further refine science goals and objectives for the AIII landing site, which will flow down into sample return requirements that may be different from those in the AIII SDT report.
- **The CaRI team confirms the assumptions in the xEVA analysis of tools and containers for the AIII SDT report candidate program.** The provided xEVA design reference volume and mass estimates are appropriate interpretations of the candidate nominal sample program and provide a reasonable envelope for a variety of sample types and containers.
- **The CaRI team finds that due to immature understandings of sample tools and containers, the assumptions used by the SDT to create the candidate science programs are not valid.** The Artemis III Science Team will need to revisit the sample program, along with their science goals, and make appropriate trades to fit into the downmass and upmass allocations. This exercise would be aided by a "menu" of tools and containment options from the xEVA tools team.

References and Attachments:

CaRI Request 008
CAPTEM report - Analysis of Lunar Sample Mass Capability for the Lunar Exploration Architecture.pdf
Lawrence & Mitchell - Artemis_sustaining_phase_mass_analysis_v7_11292021.pdf